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Feasibility study of offshore wind turbine installation in Iran compared with the world

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ABSTRACT

Renewable energies have potential for supplying of relatively clean and mostly local energy. Wind energy generation is expected to increase in the near future and has experienced dramatic growth over the past decade in many countries. Offshore winds are generally stronger and more constant than onshore winds in many areas. The economic feasibility for utilization of offshore wind energy depends on the favorable wind conditions in the area. The present paper analyses offshore wind speed in global scale and also studies feasibility of introducing this technology for harnessing wind in Persian Gulf, Caspian Sea, Urmia Lake and Gulf of Oman. Wind speed data were collected from different sources. The ocean surface winds at a 10 m height from satellite passes as processed by NOAA/NESDIS, from near real-time data collected by NASA/JPL's Sea Winds Scatterometer aboard the QuikSCAT. Development of renewable energy is one of priority research goals in Iran. There are many installed wind turbines in suitable regions like Manjil and Binalood, but there has not been any offshore wind installation yet in Iran. It is suggested that policy makers to invest and pay more attentions toward harnessing renewable energy sources like offshore wind in Persian Gulf and Gulf of Oman in southern parts of Iran.

Contents

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1. Introduction

Nowadays, the rapidly increasing demand for electrical energy and the high restriction on pollution levels have led to an increasing interest in large-scale utilization of renewable energies like wind across many countries including Iran [1]. Offshore wind power has a large potential as a vast resource for delivering clean and abundant energy on a global scale. However, the siting of offshore wind farms in the coastal zone has negative effects on the seascape [2]. Offshore wind power has attracted attention around the world, and the development of offshore wind power development is to argue for a direction. At present, offshore wind power technology has become more and more mature and has entered the large-scale development phase [3]. In fact, contribution of the wind energy for production of electricity in Iran is very low [4]. The use of renewable energy has started to be an interesting issue for people and also governments in Middle East, especially in Iran where all different types of renewable energy sources (RES) are available and also possible to implement for gaining required energy [5]. Development in wind energy towards higher nominal power of the wind turbines is related to the moving of the turbines to better locations. First, there was a shift from onshore to offshore. Further, there have been studies toward moving from coast to the deep water, which requires floating windmills.

Wind energy has experienced dramatic growth over the past decade. A small fraction of this growth has occurred offshore, but as the best wind resources become developed onshore, there is increasing interest in the development of offshore winds [6]. Offshore wind farms promise to become an important source of energy in the near future: it is expected that by the end of this decade, wind parks with a total capacity of thousands of megawatts will be installed in European seas. This will be equivalent to several large traditional coal-fired power stations. Plans are currently advancing for such large-scale wind parks in Swedish, Danish, German, Dutch, Belgian, British and Irish waters and the first such parks are currently being constructed at Horns Rev, and off Denmark's western coast, in the Danish part of the Baltic coast [7].

The world's first offshore wind farm was built in 1991 in Denmark and offshore wind energy has become an increasingly attractive option due to the enormous energy potential associated with the vast offshore areas. Optimal solutions for offshore wind energy are expected to differ from its onshore counterpart, and successful adapted solutions might result in great reductions of costs, making this form of energy more competitive and its deployment more important in the coming years. As such, it is expected to be the next big step in wind energy development. This technology has up to now been exclusive to Europe, but North America, where conditions differ from those of the existing European offshore wind parks, is now appearing as an important upcoming player [8].

Energy planners have shifted their attention towards offshore wind power generation and the decision is supported by the public in general, which in the literature has a positive attitude towards offshore wind generation. However, globally only a few offshore wind farms are operating. As more wind farms start operating and more people become experienced with especially the visual impacts from offshore wind farms, the public positive attitude could change if the experienced impacts are different from the initially perceived visual interference [9].

Offshore wind farm is constructed in general on the continental shelf area which is about 10 km away from the coast and 10 m deep. Compared with land, offshore wind turbines must be fixed on the seabed, which demand a more solid supporting structure. Submarine cables are needed for transmission of electricity, and special vessels and equipments are required for building and maintenance work [3]. Offshore wind energy competes with both onshore wind energy and conventional fossil-fueled electricity. Onshore wind power and natural gas fired power are the two fastest growing segments of the electricity market. Coal power is the largest current producer of electricity in the U.S. Offshore wind will thus displace coal, natural gas or onshore wind [6].

It has to be noted though that the current market share of offshore wind turbines is still small (1.3%). In 2008, about 360 MW were installed offshore compared to 27,000 MW in total [10]. In some countries and regions, however, offshore wind power is expected to grow at much higher rates than onshore wind power. According to a scenario of the European Wind Energy Association, investments into offshore turbines in Europe will surpass onshore investments after 2020 [11].

At the end of 1997 the world wide onshore capacity of grid connected wind power plants has reached the value of more than 7200 MW with an annual electricity generation of 14 TWh and annual rate of installation of 1300 MW. More than 60% of the above values (4450 MW and 8.5 TWh) with an annual rate of installation of 950 MWe are attributed to European and Mediterranean countries [12].

Onshore wind turbine technology is evolving rapidly driving the development of the offshore turbines with their own specific

characteristics of reliability in the harsh environmental conditions of open seas [12,13]. In Denmark for example, 20% of the electricity is produced from wind, and plans are towards reaching 50%. As space is becoming scarce for the installation of onshore wind turbines, offshore wind energy, when possible, seems as a good alternative [8].

Over the past 10 years, the onshore wind industry in the U.S. has grown dramatically and as a result developers, citizens and the U.S. Congress have expressed interest in the development of an offshore wind industry [6]. Efforts to harness the energy potential of Earth's ocean winds could soon gain an important new tool: global satellite maps from NASA. Scientists have been creating maps using nearly a decade of data from NASA's QuikSCAT satellite that reveal ocean areas where winds could produce wind energy.

The new maps have many potential uses including planning the location of offshore wind farms to convert wind energy into electric energy [14].

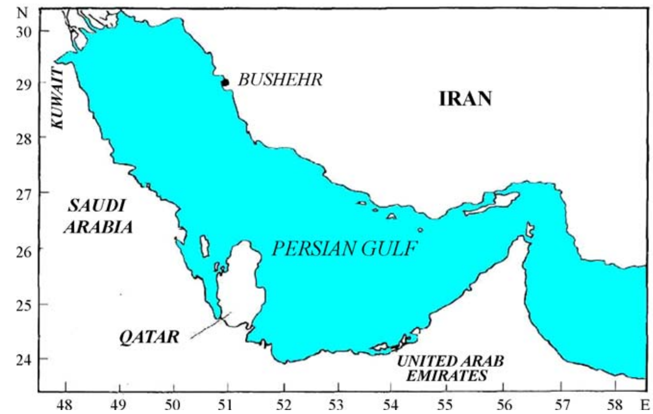


Fig. 1. Persian Gulf map [18].

2. Geographic profile of Iran

Iran (Persia) is situated in south-western Asia and borders the three CIS states, the Republic of Armenia, the Republic of Azerbaijan, and the Republic of Turkmenistan, as well as the Caspian Sea to the north, Turkey and Iraq to the west, the Persian Gulf and the Gulf of Oman to the south, Pakistan and Afghanistan to the east [4,15]. There are four different available locations for harnessing offshore wind such as: Persian Gulf, Caspian Sea, Urmia Lake and Gulf of Oman.

There has not been a serious research about offshore wind energy development yet in Iran, mainly due to lack of technology, need for expensive crane vessels, high cost of investment and lack of offshore wind atlas. Iran has been trying to harness wind in areas with good potential, but offshore is not in priority yet.

2.1. Persian Gulf

The Persian Gulf (Fig. 1) is an important military, economic and political region owing to its oil and gas resources and is one of the busiest waterways in the world. Countries bordering the Persian Gulf are Iran, United Arab Emirates, Saudi Arabia, Qatar, Bahrain, Kuwait and Iraq [16,17]. Iran is located in north of Persian Gulf and populated ports are Bushehr, Bandar Abbas, Khorramshahr and Abadan. There are also many islands in Persian Gulf like Kish, Lavan, Khark, Gheshm, Big Tunb and Small Tunb.

The Persian Gulf, in the Southwest Asian region, is an extension of the Indian Ocean located between Iran and the Arabian Peninsula [19]. Historically and commonly it is known as the Persian Gulf. The Persian Gulf has many good fishing grounds, extensive coral reefs, and abundant pearl oysters, but its ecology has come under pressure from industrialization, and in particular, petroleum spillages during the recent wars in the region [20]. The Persian Gulf is certainly one of the most vital bodies of water on the planet, as gas and oil from Middle Eastern countries flow through it, supplying much of the world's energy needs [21]. This inland sea of some 251,000 km^2 is connected to the Gulf of Oman in the east by the Strait of Hormuz; and its western end is marked by the major river delta of the Shatt al-Arab, which carries the waters of the Euphrates and the Tigris rivers. Its length is 989 km, with Iran covering most of the northern coast and Saudi Arabia most of the southern coast. The Persian Gulf is about 56 km wide at its narrowest, in the Strait of Hormuz. The waters are overall very shallow, with a maximum depth of 90 m and an average depth of 50 m [20]. Extensive shallow regions, less than 20 m deep, are found along the coast of United Arab Emirates (hereafter referred to as Southern Shallows), around Bahrain, and at the head of the Persian Gulf. Deeper portions, bigger than 40 m deep, are found along the Iranian coast continuing into the Strait of Hormuz, which has a width of 56 km and connects the Persian Gulf via the Gulf of Oman with the northern Indian Ocean [16].

During the daytime, in a calm atmosphere (absent of gradient wind), solar radiation heats up the land surface more rapidly than the water surface, causing a horizontal temperature gradient between the land and sea surface air. The air over the land heats up and hence expands more rapidly than the air over the sea. Due to the hydrostatic conditions, the vertical pressure gradient is greater in the cooler air over the water than in the warmer air over the land. This means that, at a given height, the pressure is higher over the land than over the water. This pressure gradient produces a slight flow of air from the upper levels above the land to the upper levels above the sea. This leads to an increase in the pressure over the sea, so that air subsidence occurs. Departure from hydrostatic equilibrium leads to the flow from the sea to the land, in the lower level. This is called the sea breeze. At nighttime the reverse process occurs and a land breeze takes place. The onset of the sea breeze is usually marked by an increase in wind speed, a decrease in temperature and an increase in humidity. If a gradient wind exists, the effects of the sea breeze may be more difficult to detect. Sea and land breezes occur more frequently and with greater regularity in the tropics than in the middle and high latitudes [22]. Sea breeze speed usually ranges between 6 and 10 m/s and from 3 to 5 m/s for a land breeze. The land breeze is always weaker than the sea breeze. The on/off shore extent of the sea breeze is about 10–20 km [23].

Fig. 2 shows that the wind speed at 10 m above sea level (V10) varies between 0.34 and 10.83 m/s with a characteristic diurnal oscillation. The lowest wind speed occurred about midnight and the highest speed around noon. The markings on the time-axis are made at 24-h intervals (starting on 15 July), in order that the diurnal pattern can be easily discernible.

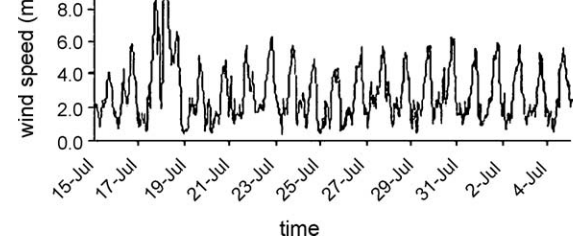


Fig. 2. Hourly time series of wind speed (V10) against time (24-h interval) [23].

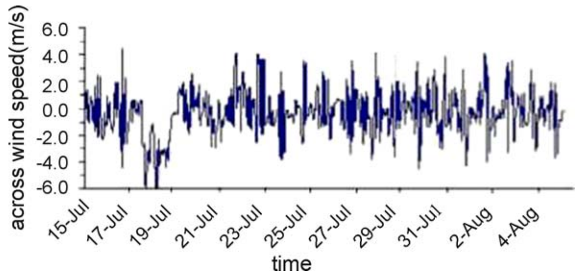


Fig. 3. Hourly time series of onshore wind against time (24-h interval) [23].

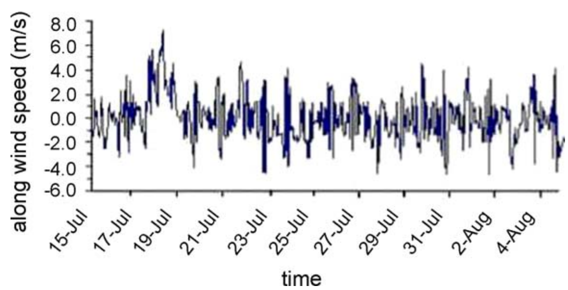


Fig. 4. Hourly time series of along shore wind against time (24-h interval) [23].

In Figs. 3 and 4 wind speeds are resolved into two components, along and across the shore. Positive (negative) values (Fig. 3) indicate a sea (land) breeze. These figures show that the sea breeze occurs during the day and the land breeze occurs at nighttime.

The diurnal variations of wind characteristics in this area, especially near the coastal zone, are normally attributed to land and sea breeze effects. Wind speed associated with the land–sea breeze is less than 6 m/s, but that of the sea–land breeze is greater. The change in wind speed and direction is almost simultaneous.

Table 1
Conversion of Knots to mph and m/s.

Knots	mph	m/s
10	11.5	5.2
20	23.0	10.3
30	34.5	15.5
40	46.0	20.7
50	57.5	25.9

Observed winds (V10) behave as land and sea breezes, with the minimum speed occurring around midnight and the maximum around noon. The wind speed varied from 0.34 to 10.38 m/s.

Tectonic driven subsidence deepened the seafloor of the Strait on its southern side (200–300 m depths are seen in some localized seafloor depressions) and produced a 70–95 m deep trough along the Iranian side of the eastern part of the Persian Gulf. A southward widening channel leads from the Strait south across a series of sills (water depth of 110 m) and shallow basins to the shelf edge [16,24]. The narrow Strait of Hormuz restricts water exchange between the Persian Gulf with the northern Indian Ocean. The Persian Gulf is a semi-enclosed, marginal sea that is exposed to arid, sub-tropical climate. It is located between latitudes 24–30N, and is surrounded by most of the Earth's deserts [16,25].

Ideally, offshore wind farms should be located in areas where winds blow continuously at high speeds. The new research identifies such areas and offers explanations for the physical mechanisms that produce the high winds [26]. The accurate wind atlas for Persian Gulf and Gulf of Oman could be easily drawn from

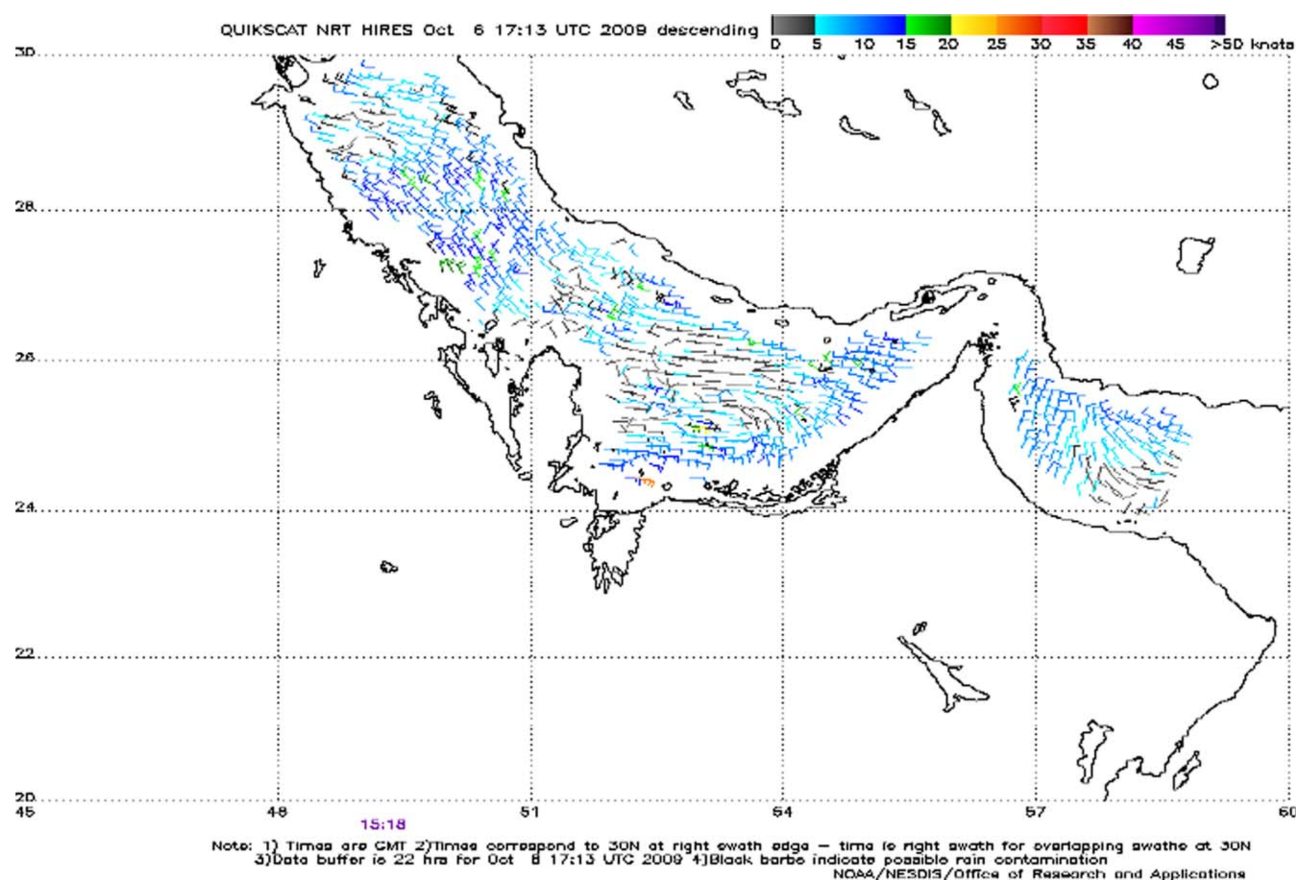


Fig. 5. Wind speed map of Persian Gulf for 6th of October 2009 [27].

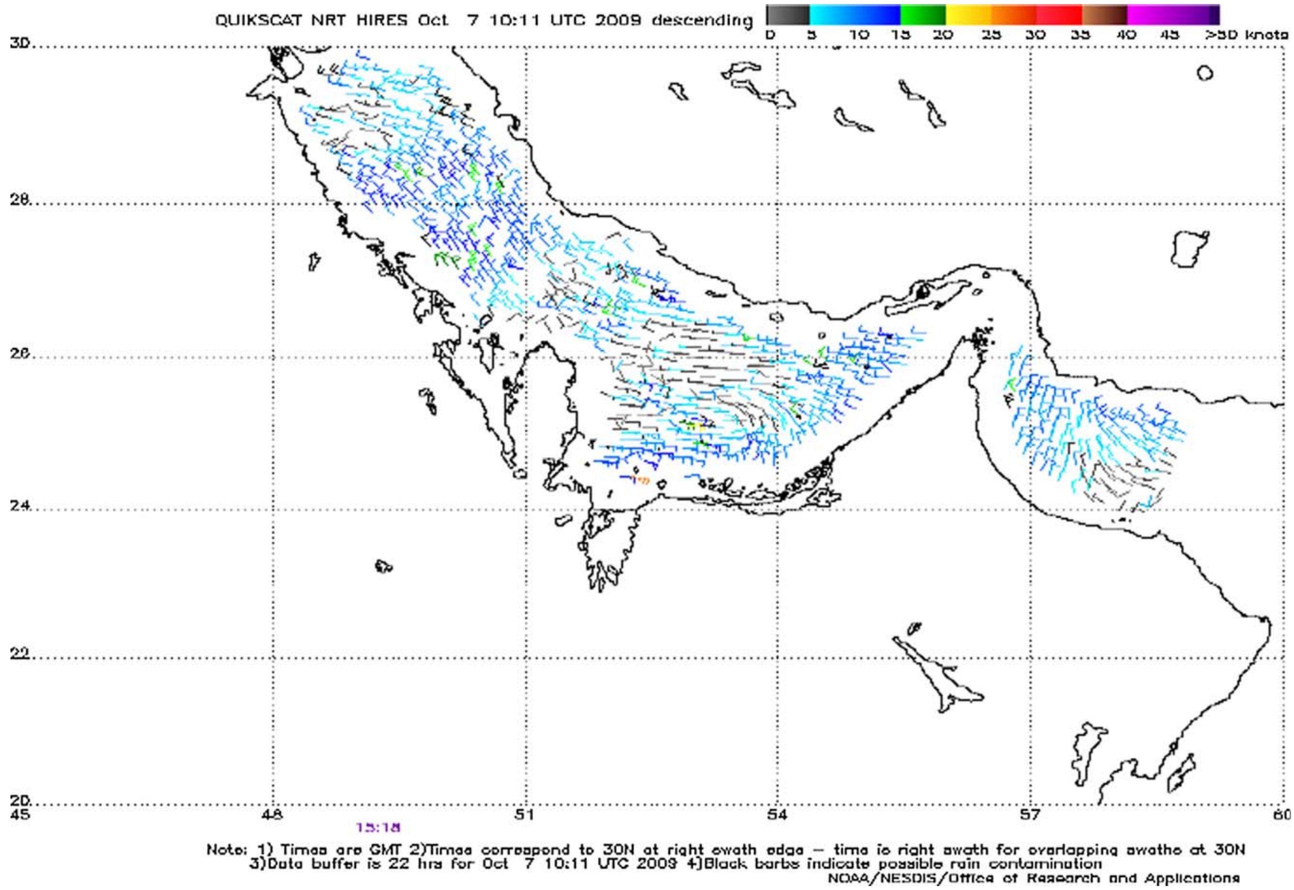


Fig. 6. Wind speed map of Persian Gulf for 7th of October 2009 [27].

the data of QuickSCAT. There are some locations which are suitable for offshore wind turbines in south of Iran, but total hours of wind occurrence in year must be obtained for this purpose. Furthermore, these two figures show only data for October 6th and 7th of 2009.

Wind speeds in most of the offshore maps are expressed in Knots, for conversion of the Knots to mps or m/s it is more convenient to use Table 1. Mean wind speed at 10, 30 and 40 m height from 2006 to 2008 for Kish Island in Persian Gulf was 4.52, 5.05 and 5.34 m/s respectively [28].

Wind speed in coastal areas of Persian Gulf (Figs. 5 and 6) is almost 10 Knots which is equivalent to 5 m/s. This speed is not good for larger wind turbines. But, there are some regions inside the Persian Gulf with wind speed of up to 40 Knots which is equivalent to 20.7 m/s and is good for installation of turbines. These data are only for 2 days, but more analysis must be done in order to get accurate results. Fig. 10 gives us the monthly global wind speed in which the average for Persian Gulf is 7 m/s. It is possible to harness wind in those areas, but total hours of wind must be provided for further decisions. Saudi Arabia has done a satisfactory research work regarding of wind behavior in Persian Gulf which will be discussed in this paper too.

2.1.1. Wind storms in the Persian Gulf

The most known weather phenomenon in the Persian Gulf is the Shamal, a northwesterly and northerly wind which occurs year-round [16,25]. Shamal produces the most widespread hazardous weather known in the region [29]. In winter, the Shamal is of intermittent nature associated with the passage of synoptic weather systems, but it seldom exceeds a speed of 10 m/s. The summer Shamal is of continuous nature from early June through to July. Seasonal variations of the Shamal are associated with the relative strengths of the Indian and Arabian thermal lows [16,17]. They are caused by the presence of a large pressure gradient that develops behind a cold front passage. Upper level subsidence in the high-pressure cell behind the front reinforces the low-level northwesterly winds. Moderate to strong winds can raise desert surface material and reduce visibility. During a Shamal, winds typically reach 30–40 Knots near the surface during the daytime [29]. A common phenomenon with Shamal wind events is de-coupling from the surface layer (particularly at nighttime), so that the wind aloft (several hundred meters above the surface) is very strong, while the wind at the surface is moderate to light. In these cases, the wind speed typically peaks at elevations between 500 and 1000 m above the surface and the vertical profile of wind speed between the surface and the level of maximum wind speed can be unusually steep [29].

2.1.2. Wind behavior data for Persian Gulf

The behavior of wind speed and direction over the Persian Gulf was studies by Saudi Arabia in 2009. This is the most accurate recent work which was done for Persian Gulf.

The data used for the analysis covers the years 1960–2007, provided by the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). The study area which covers 24°N/29°N–48°E/56°E has with 1° resolution a total number of 36 grid points over water and 9 points in land. The data provided by ICOADS data is typically collected from merchant ships that pass through the channel. The data is statistically formatted for each month of each year, with respect to longitude and latitude. The analysis of mean monthly wind speed and direction are shown in Figs. 7 and 8 reveal that the direction of wind speed is North-West over the year. Winter wind is stronger than summer wind. This season lasts from

November to March. Comparatively, the summer wind is weak and the season lasts from the beginning of June to the end of August. The average wind speed over some area of Persian Gulf shore for the months of November to March are 5.39, 7.27, 7.35, 6.26 and 5.85 m/s respectively. Similarly, in the same location over the months of June and July the average wind speed is 6.60 and 5.96 m/s respectively. Although most of the Persian Gulf areas in the summer have low wind speed (there exist other areas of moderate wind speed such as central Persian Gulf). The general conclusion from the analysis of mean monthly wind speed supports that stronger wind speeds are observed over the months of November to February. This study is an initial step suggesting typical wind behavior over the Persian Gulf. The study shows that with the current amount of data, we have seen high trends of wind speed. Over the study area (45 grid points) months such as November, December, January and February have shown the highest wind speeds. The averages are 5.39, 7.27, 7.35 and 6.26 m/s respectively. This also leads to safe state that a wind farm is a prospective renewable energy resource and wind behavior over the Persian Gulf will supply efficient wind resources to justify the assets [127]. It could be concluded from Figs. 7 and 8 that Western part of Persian Gulf has the highest wind speed in June. Ports of Bushehr and Kangan are the nearest populated areas which could benefit from offshore wind in months of May, June and December. Clearly, these ports could be supplied with less wind energy (4 m/s) for months of January, February and March. Eastern part of Persian Gulf has the minimum offshore wind speed. Kish Island, Qeshm Island and port of Bandar Abbas are the most important cities that are located in Eastern part of Persian Gulf. It should be noted that Persian Gulf with average potential of wind energy is not a perfect zone for offshore wind farms. There are 34 islands which belong to Iran in Persian Gulf. Most of the Iranian Islands in Persian Gulf are

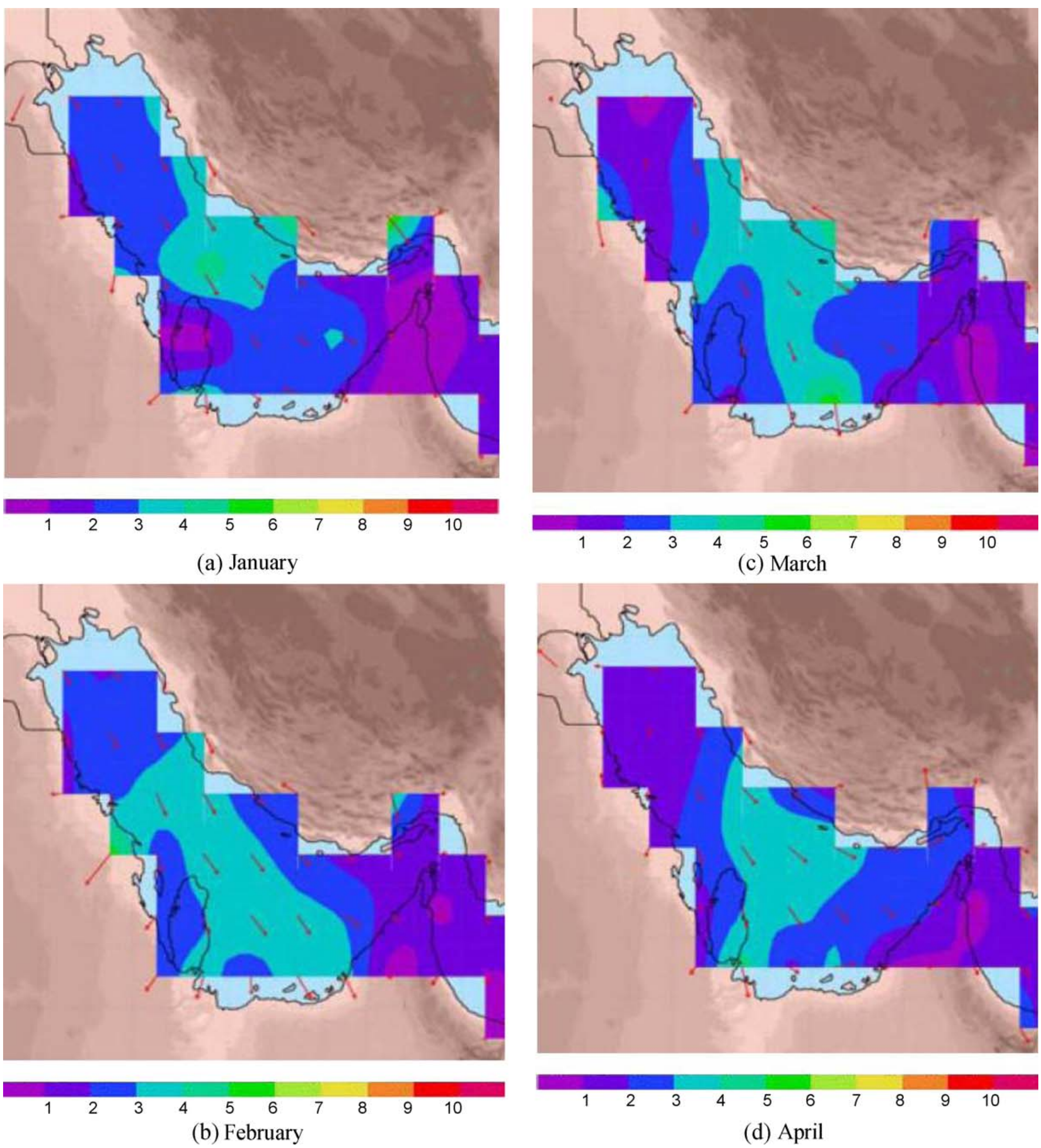


Fig. 7. Monthly mean wind speed (m/s shaded) and direction (red arrows) from January to June [127]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

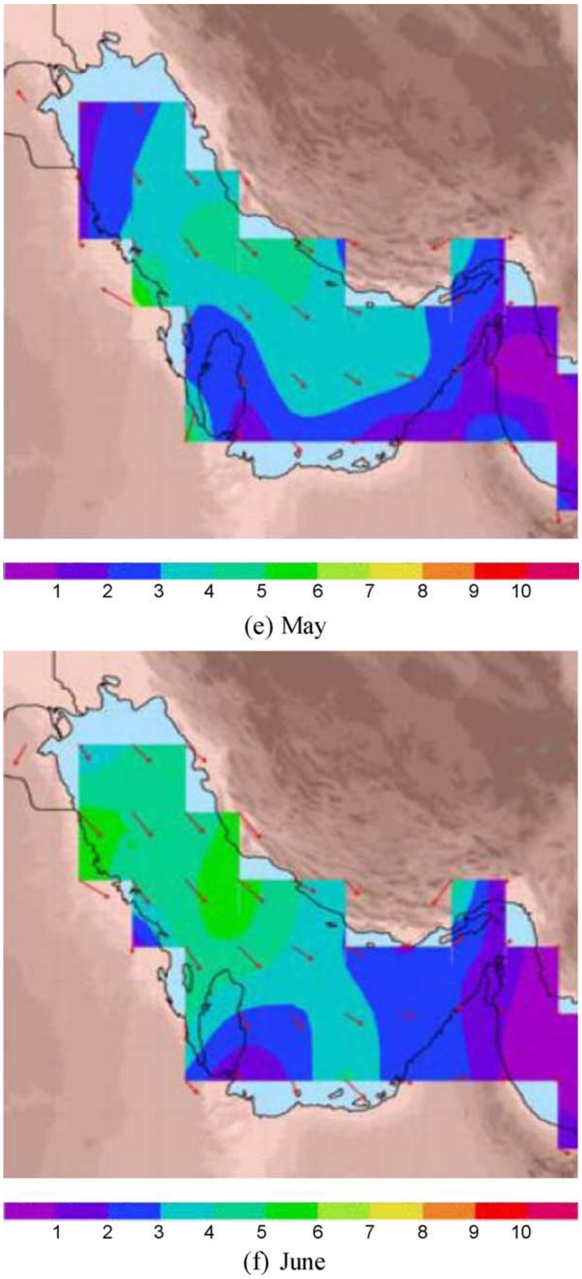


Fig. 7. (*Continued*).

located in Eastern parts with low wind speed. Bahrain, Kuwait, Saudi Arabia and UAE have 9, 9, 1 and 3 islands respectively in Persian Gulf.

2.2. Caspian Sea

The Caspian Sea (Fig. 9) is the largest enclosed body of water on Earth by area, variously classed as the world's largest lake or a full-fledged sea [30,31]. It has a surface area of 371,000 km^2 (143,244 sq mi) and a volume of 78,200 km^3 (18,761 cu mi) [32].

It is an endorheic basin (it has no outflows), and is bound by northern Iran, southern Russia, western Kazakhstan and Turkmenistan, and eastern Azerbaijan. It was perceived as an ocean by its ancient coastal inhabitants, presumably because of its saltiness and seeming boundlessness. It has a salinity of approximately 1.2%, about a third the salinity of most seawater [33]. The southern part includes the South Caspian Depression with its deepest point being 1025 m below the surface [29].

The Caspian is divided into three distinct physical regions: Northern, Middle, and Southern Caspian [35]. The North–Middle boundary is the Mangyshlak threshold, which runs through Chechen Island and Cape Tiub-Karagan. The Middle–South boundary is the Apsheron threshold, a sill of tectonic origin [36] that runs through Zhiloi Island and Cape Kuuli [37]. The Garabogazköl bay is the saline eastern inlet of the Caspian, which is part of Turkmenistan and at times has been a lake in its own right due to the isthmus which cuts it off from the Caspian [33].

Divisions between the three regions are dramatic. The Northern Caspian only includes the Caspian shelf [38] and is characterized as very shallow; it accounts for less than 1% of the total water volume with an average depth of only 5–6 m. The sea noticeably drops off towards the Middle Caspian, where the average depth is 190 m [37]. The Southern Caspian is the deepest, with a depth that reaches over 1000 m. The Middle and Southern Caspian account for 33 and 66% of the total water volume, respectively [35]. The northern portion of the Caspian Sea typically freezes in the winter, and in the coldest winters, ice will form in the south. Over 130 rivers provide inflow to the Caspian, with the Volga River being the largest. The Caspian also has several small islands; they are primarily located in the North and have a collective land area of roughly 2000 km^2 [33,39].

In the region of the Apsheronian Peninsula (Republic of Azerbaijan) the average yearly wind velocity reaches 6–7 m/s. The dominant northern winds reach 25–30 m/s. To the south of Apsheron the average yearly velocity of the wind decreases and in Lenkoran region it equals 2–3 m/s. The region of Astara which is in the border of Iran and Azerbaijan has average yearly wind velocity of 2.7 m/s [40]. There are some important factor which should be considered regarding the offshore wind installation in southern part of the Caspian Sea which is located in north of Iran. First, the wind speed in mentioned area is low. Second, the southern part includes deep water level in which the South Caspian Depression with its deepest point being 1025 m below the surface. It is not feasible for offshore wind turbine installation in deep areas, because regular wind turbines are suitable for depths of up to 200 m. Also, floating wind turbine systems are at their early research works by scientists and it does not seem to be feasible for depths of more than 1000 m.

Ideally, offshore wind farms should be located in areas where winds blow continuously at high speeds. The new research identifies such areas and offers explanations for the physical mechanisms that produce the high winds [26]. Wind speed in coastal areas of Caspian Sea (Figs. 10 and 11) is almost up to 10 Knots which is equivalent to 5 m/s. This speed is not good for offshore wind installation. There are some regions inside the Caspian Sea with same speed, but we should consider low speed of wind and also high depth of water which both are not feasible for installation of offshore wind turbine. These data are only for 2 days, but more analysis must be done in order to get accurate results. Fig. 10 gives us the monthly global wind speed in which the average for Caspian Sea is 5 m/s. It is not a good region for offshore wind turbine installation even in areas with lower water depth.

2.3. Gulf of Oman

Gulf of Oman is located in southeastern part of Iran with good potential of wind in most of its regions (Fig. 12). Important ports along its shore are Chahbahar and Jask. Mean wind speed at 40 m height from 2006 to 2007 for city of Jask in Hormozgan province (North of Gulf of Oman) was 4.37 m/s. While mean wind speed at 40 m height from 2008 to 2009 for city of Chahbahar in Sistan and Baluchestan province (North of Oman Gulf) was 5.03 m/s [28].

Ideally, offshore wind farms should be located in areas where winds blow continuously at high speeds. The new research identifies such areas and offers explanations for the physical mechanisms that produce the high winds [26]. Figs. 7 and 8 show that North-West of Oman Gulf is not suitable for offshore wind turbines to provide electricity.

Fig. 10 shows a rough estimate for monthly wind speed, but it shows that there is not wind speed of more than 10 m/s in this area. It is possible to harness wind speed of up to 9 m/s in some areas of Gulf of Oman. It goes without saying that depth of water in this region is less than 300 m which is feasible for offshore turbine installation. Fig. 13 shows that there is possibility of harnessing winds of up to 10 m/s inside the Gulf of Oman, but this figure is only for 7th of October 2009. More accurate survey must be done in order to install offshore wind turbines in South-Eastern waters of Iran.

2.4. Urmia Lake

Urmia Lake is located between latitude 37°N to 38.5°N and longitude 45°E to 46°E. Urmia Lake is the 20th large lake and the second hyper saline lake in the world. The Urmia Lake covers an area average of 5100 km^2. The maximum depth and average depth of this lake respectively are 16 and 5 m. Urmia Lake is listed as a biosphere reserve by UNESCO. Also, it is a national park in the national level [100].

Urmia Lake coastlines extracted from ETM+ and TM imagery. These images have been acquired in 1989 and 2001 years (Figs. 14 and 15).

The coastline maps show that the coastline has small changes from 1989 to 1998 year. These small changes in Urmia Lake coastline are perpetual. But the coastline has been changed greatly from 1998 to 2001 year. These great changes have happened as the

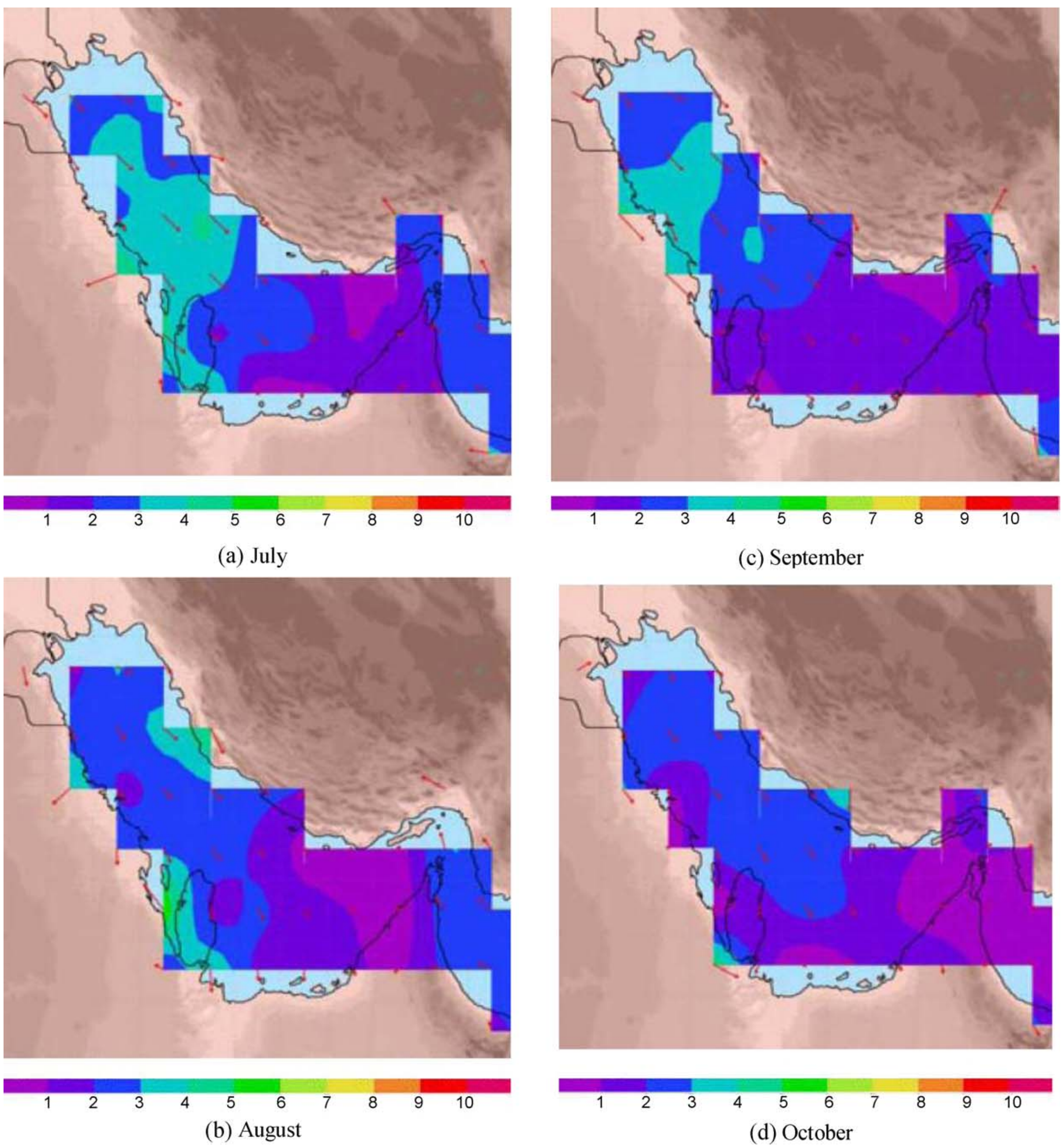
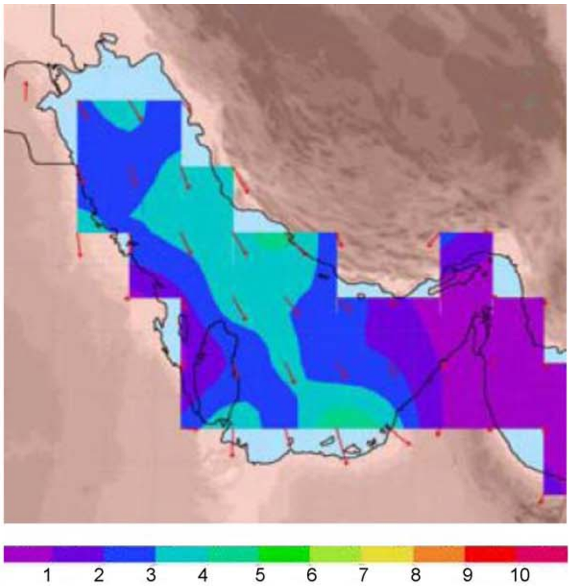
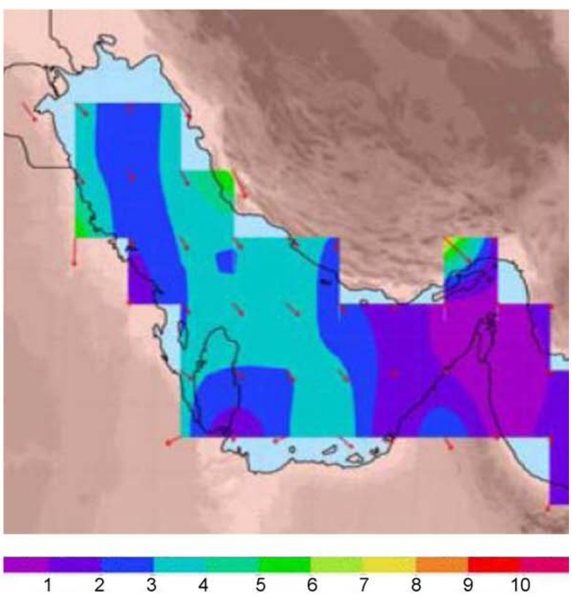


Fig. 8. Monthly mean wind speed (m/s shaded) and direction (red arrows) from July to December [127]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)



(e) November



(f) December

Fig. 8. (*Continued*).



Fig. 9. Caspian Sea.

result of 3 m decrease in height of water of Urmia Lake [100]. Urmia Lake has an area of 5100 km^2 and average depth of 5 m. Economically, it is a very good site for offshore wind turbine installation. But accurate wind data of Urmia must be collected for this purpose. Iranian renewable energy organization has been busy on research about inland sites for wind turbines, but they plan to work and do research toward offshore winds in the future.

Ideally, offshore wind farms should be located in areas where winds blow continuously at high speeds. The new research identifies such areas and offers explanations for the physical mechanisms that produce the high winds [26]. Energy planners have shifted their attention towards offshore wind power generation and the decision is supported by the public in general [42]. According to data of synoptic stations for city of Tabriz in 1991, the city was exposed to wind with minimum speed of 18 and maximum of 50 m/s in 168 days. The highest wind speed was 50 m/s in May and the lowest in December and January with speed of 18 m/s. According to data of synoptic stations for city of Urmia, the city was exposed to wind with minimum speed of 7 and maximum of 16 m/s in 164 days. The highest wind speed was 16 m/s in April and March and the lowest in January and February with speed of 7 m/s. The average wind speed in Urmia was 10.5 m/s [43]. The closest big cities to the Urmia Lake are Tabriz and Urmia with good potential of harnessing wind. Therefore, it is not economically feasible to consider building the offshore wind turbines inside Urmia Lake.

3. World offshore status

The first offshore wind farm began operating in 1991; by the end of 2008 there were approximately 1500 MW of installed capacity. By 2009 or 2010 the wind capacity in Europe is expected to grow by another 1500 MW [44], and by 2015, the rate of growth of the European offshore industry is expected to be 1700–3000 MW per year [45,46]. The Danish government's tender to build in 2 blocks of the sea about 16 MW of wind power demonstration was projected in 1997, and now they have been put into operation [3].

Key drivers for offshore wind energy success are various policy schemes that promote technology development and diffusion in countries such as Denmark (Fig. 16), Germany, Spain, the US or India [47,48–50].

The first offshore wind generating international conference and exhibition was held in Copenhagen from October 26 to 28 in 2005 [3].

As of 2007, a series of offshore wind energy projects had been realized. In Denmark, for example, eight offshore wind parks with a total capacity of about 430 MW are installed and another 420 MW planned. In the UK, offshore wind turbines of 400 MW were running and more than 8000 MW planned or under construction [52]. German offshore waters may even hold more than 30,000 MW if current plans will be realized. Some national plan figures for offshore wind power even exceed existing onshore capacity [47].

Five wind farms are functioning in the internal seas of Netherlands, Denmark, Sweden; however such siting is mostly to be considered as semi-offshore condition, Wind farms in real

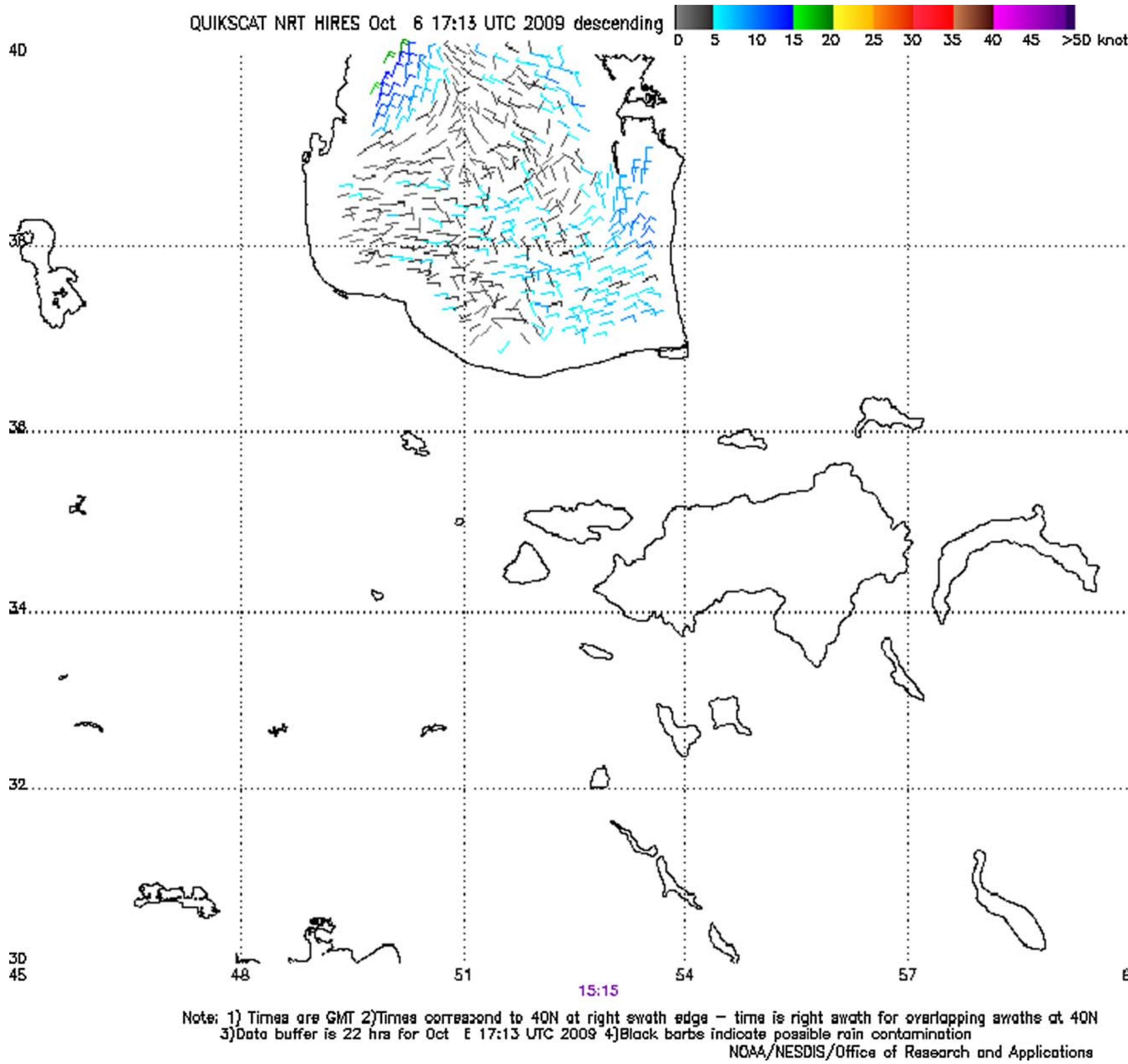


Fig. 10. Wind speed map of Caspian Sea for 6th of October 2009 [27].

offshore sites, open seas with waves and water depth over 10 m, are now proposed in North Sea at 10–20 km off the coasts of Netherland, Denmark using large size wind turbine (1–2 MW) [12]. Ideally, offshore wind farms should be located in areas where winds blow continuously at high speeds. The new research identifies such areas and offers explanations for the physical mechanisms that produce the high winds. An example of one such high-wind mechanism is located off the coast of Northern California near Cape Mendocino. The protruding land mass of the cape deflects northerly winds along the California coast, creating a local wind jet that blows year-round. Jets are formed from westerly winds blowing around Tasmania, New Zealand, and Tierra del Fuego in South America, among other locations. Areas with large-scale, high wind power potential also can be found in regions of the mid-latitudes of the Atlantic and Pacific oceans, where winter storms normally track [26].

3.1. Europe

The status of offshore wind energy is very different in Europe and North America. At the end of 2006, Europe had operating wind farms in Denmark (398 MW), United Kingdom (304 MW), Ireland (25 MW), Sweden (23.3 MW) and the Netherlands (136 MW). It represented then 1.8% of the installed wind energy, but 3.3% of the wind energy production [53]. Fig. 17 shows a map of the existing and planned wind turbines in North West Europe, where the development has been concentrated up to now [8]. Offshore wind energy development is taken very seriously in Europe. In February 2007, it was given high priority when European member states made a firm commitment to increase the total share of renewable in primary energy consumption to 20% by 2020 [54]. The target is to reach 50 GW of offshore wind energy by 2020. This is a progression for the next 13 years that would correspond to the development seen in the onshore sector in the last 13 years [53].

Denmark with total amount of 214 installed offshore wind turbines is the leading country in the world (Table 2). For majority of installed turbines, distance to the shore is less than 20 km. Depth of water for most of the offshore wind sites are less than 12 m, but there are only 10 turbines installed in location with 20 m depth.

Wind power is the fastest growing source of renewable energy in Europe, so it is no surprise to learn that Denmark is launching

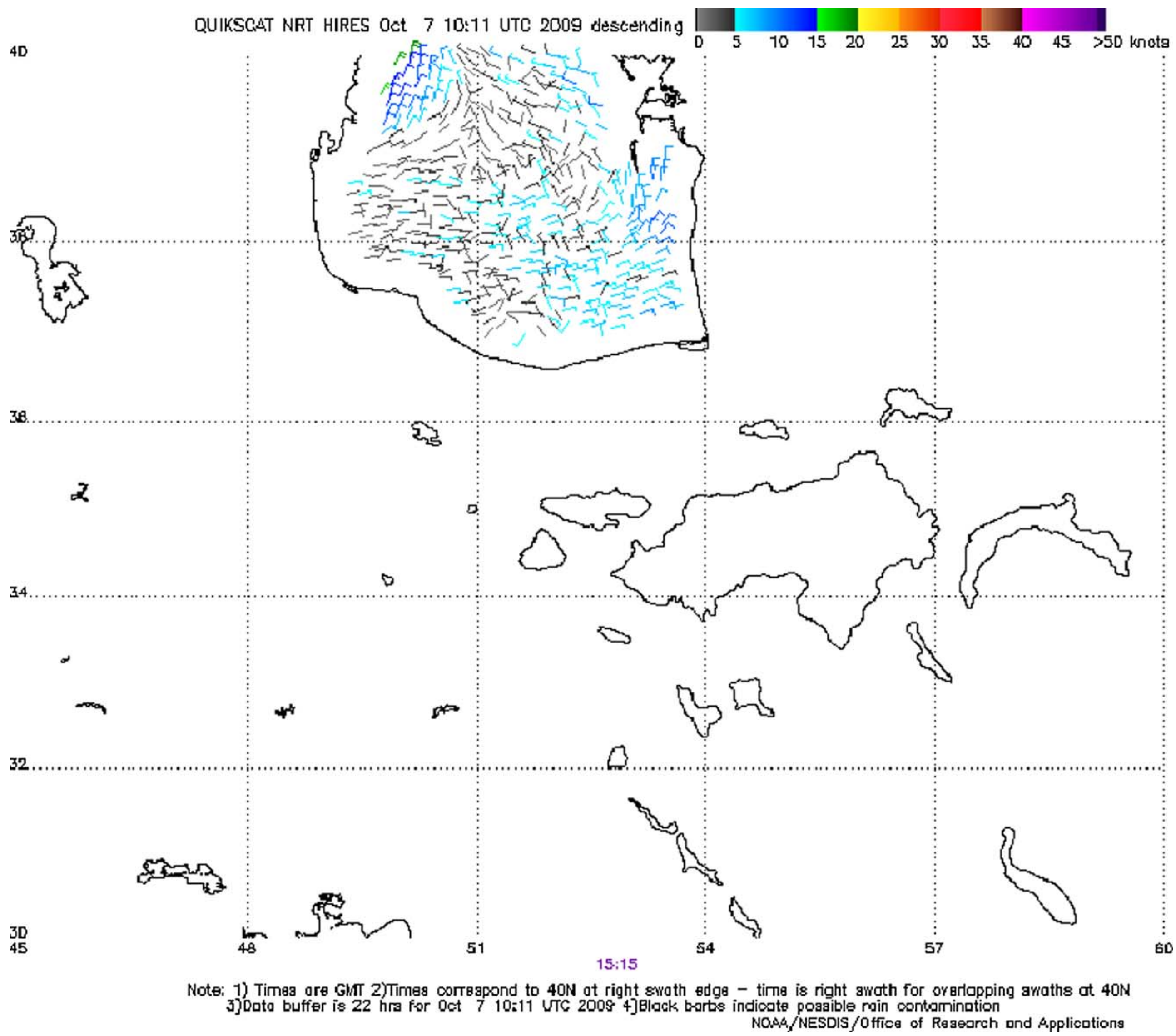


Fig. 11. Wind speed map of Caspian Sea for 7th of October 2009 [27].

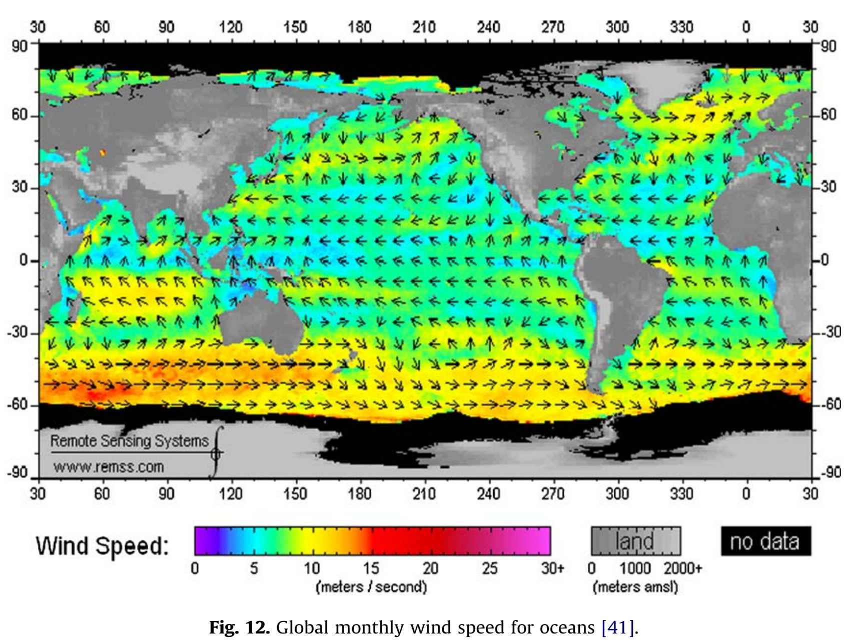


Fig. 12. Global monthly wind speed for oceans [41].

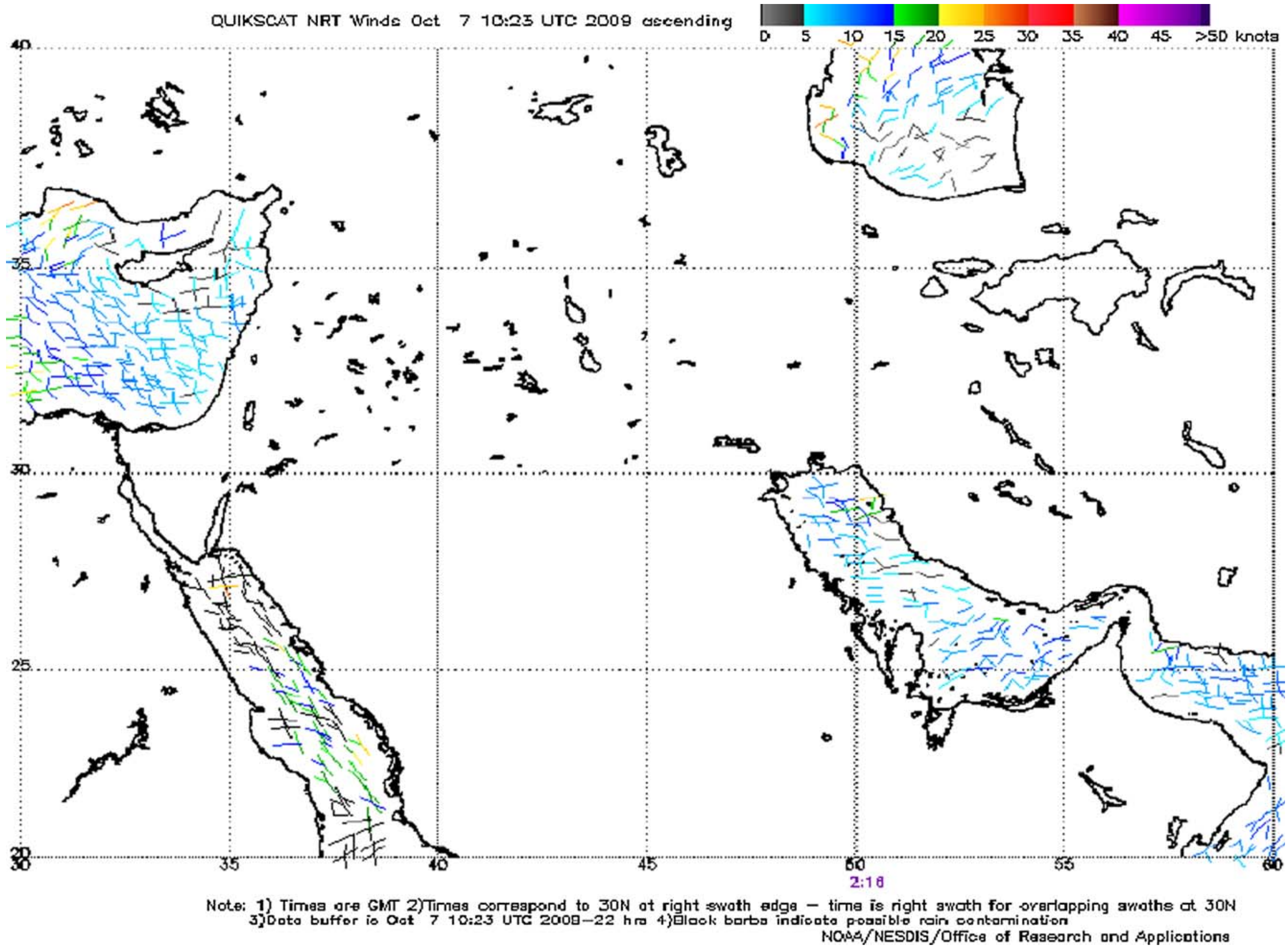


Fig. 13. Wind speed map of Gulf of Oman for 7th of October 2009 [27].

the world's biggest offshore wind farm on October 2009. Using 91 turbines scattered across 35 km^2, the Horns Rev 2 farm, built by Danish utility company Dong Energy, will be able to produce 209 MW of power – enough for a staggering 200,000 homes. With a price tag of $1 billion, Horns Rev is not cheap. But the project could offset some serious carbon emissions and help Europe achieve its goal of getting 20% of its power from renewable sources by 2020. If offshore wind projects continue, the European Wind Energy Association predicts that offshore turbines could produce as much as 10% of the EU's power in the next 11 years [56].



Fig. 14. Urmia Lake in June 1989 [100].



Fig. 15. Urmia Lake in August 2001 [100].



Fig. 16. Offshore wind turbines in Denmark [51].

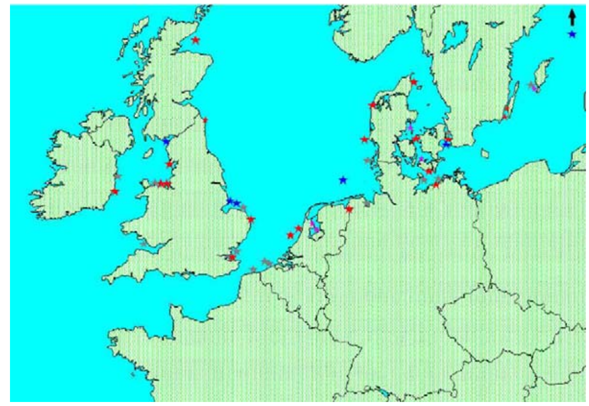


Fig. 17. Existing and planned wind farms in North West Europe, June 2007. Red: built MW turbines; purple: built small turbines; blue: under construction; grey: planned [8,55]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

United Kingdom with total amount of 149 installed offshore wind turbines is next after Denmark (Table 2). For majority of installed turbines, distance to the shore is less than 5.5 km, but there are only two turbines which are located at the distance of 25 km from the shore. Depth of water for most of the offshore wind sites are less than 23 m.

Netherlands has installed 128 offshore wind turbines in which 60 of them have been installed at the distance of 23 km from the shore with depth of between 20 and 24 m. Sweden, Ireland and Germany with total amount of 14, 7 and 2 installed offshore wind turbines respectively are other European countries in this field (Table 2).

There are some more offshore sites in Europe which are under construction (Table 3). United Kingdom with total amount of 114 is the leading country. Sweden with 48, Germany with 12 and Finland with 8 offshore wind turbines are also other active counties.

The key European markets have up to now been Denmark and the UK. Denmark was the pioneer in this field as it built the first offshore wind farm in the world in Vindeby in 1991. It has now eight operating wind farms, including the biggest one in the world, located at Horns Rev in the North sea (Fig. 18) composed of 80 turbines (2 MW) that generate enough power to meet the demand of 150,000 Danish homes. Wind conditions in this area being exceptional, the production of this wind farm is equal to rated production between 40 and 50% of the year [57]. Two upcoming farms of a capacity of 200 MW each, Horns Rev II and Rodsand, expected to be commissioned 2009/2010, will generate enough energy to power from 350,000 to 400,000 Danish homes, or 4% of the Danish electricity consumption. Wind energy might be able to produce more than 50% of the Danish electricity needs by 2025, and most of the new parks are expected to be located offshore [57]. The UK has five operating wind farms (Table 2). The development plans are huge, and as of now, leases have been allocated for parks totaling 7200 MW, corresponding to 7% of UK's electricity supply [58]. The UK has also built the demonstration farm called Beatrice [59], in a water depth of 45 m, making it the deepest wind turbine site in the world. Germany has no operating wind farm yet, but it is expected to be a key player in the years to come, as projections from the German Environment Ministry claim a target of 1100 MW by 2010, and from 12,000 to 15,500 MW by 2020 [60]. Norway does not have an operating offshore wind farm yet, but the

Table 2
Built offshore wind turbines [8].

Country	Location	Distance to shore (km)	Depth (m)	Turbine power (MW)	No. of turbines
United Kingdom	Beatrice	25	45	5	2
United Kingdom	Blyth	0.8	6–11	2	2
United Kingdom	Barrow-in-Fumess	7	21–23	3	30
United Kingdom	Burbo	6.4	1–8	3.6	25
United Kingdom	North Hoyle	6	10–20	2	30
United Kingdom	Scroby Sands	2.3	4–8	2	30
United Kingdom	Kentish Flats	8.5	5	3	30
Ireland	Arklow Bank	10	2–3	3.6	7
Netherlands	Q7-WP	23	20–24	2	60
Netherlands	Egmond Ann Zee	10	19–22	3	36
Netherlands	Lely	0.75	5–10	0.5	4
Netherlands	Irene Vornnk	0.02	5	0.6	28
Germany	Ems-Enden	0.04	3	4.5	1
Germany	Breitling	0.5	2	2.5	1
Denmark	Ny Sted	10	5–9.5	2.3	72
Denmark	Samso	3.5	20	2.3	10
Denmark	Fredenkshavan	0.2	4	3 and 2.3	1 and 2
Denmark	Ronland	0.2	1	2.3 and 2	4 and 4
Denmark	Horns Rev	14–20	6–12	2	80
Denmark	Middel Grunden	3	3–6	2	20
Denmark	Vindeby	1.5	3–5	0.45	11
Denmark	Tuno Knob	6	3–5	0.5	10
Sweden	Yttre Stengrund	5	6–10	2	5
Sweden	Utgrunden	8	7–10	1.425	7
Sweden	Bockstigen	3	6	0.5	5

Table 3
Under construction offshore wind turbines [8].

Country	Location	Distance to shore (km)	Depth (m)	Turbine power (MW)	No. of turbines
United Kingdom	Robin Rigg	9	3–21	3	60
United Kingdom	Inner Dowsing	5	10	3.6	27
United Kingdom	Lynn	5	6–13	3.6	27
Germany	Alpha Ventus	43–50	30	5	12
Sweden	Lillgrund Bank	7	4–8	2.3	48
Finland	Kemi	0.05–1		3	8



Fig. 18. Horns Rev offshore wind farm, Denmark [8,62].

company Statkraft is developing plans for a 1000 MW park in water depths of 30–60 m by 2012 [61], that would make it the deepest wind park in the world [8].

Offshore wind development in France is slow, as there is no specific legislative or administrative framework for the development of offshore wind energy, and the framework applying to offshore economic activity is not adapted to wind energy. Preparation for the first offshore wind farm in France began with a government tender in 2005, but due to long authorization procedures, construction has been delayed and is now scheduled to start in 2009 or 2010. However, there are indications that the principle of exclusion zones will no longer be applicable offshore, and work has begun on simplifying offshore planning procedures [63].

While onshore wind energy is progressing at a healthy rate, Poland does not have any offshore developments, and none are expected 2015, when about 500 MW are forecast to be developed. By 2020, offshore wind capacity could reach 1500 MW [63].

Turkey has very limited oil and gas reserves and is therefore looking at renewable energy as a means to improve its energy security and curb dependence on imported gas from Russia and Iran. A Wind Atlas of Turkey by the Turkish Energy Market Regulatory Agency (EMRA) in May 2002 indicates that the regions with the highest potential for wind speeds at heights of 50 m are the Aegean, Marmara, and Eastern Mediterranean Regions of Turkey, as well as some mountainous regions of central Anatolia [63]. There has not been a serious effort toward offshore wind installation in Turkey yet. It goes without saying that Europe is leader in offshore wind industry, but there are some European countries which have not invested in harnessing offshore wind energy. Fig. 19 shows the biggest wind farm of the world which was finished in 2009.

3.2. America

3.2.1. North America

North America is still at a planning stage concerning offshore wind energy, as it does not yet have operating offshore wind farms. The potential, however, is enormous. The areas off the US coast within a 50 nautical miles limit represent a potential of 907 GW, which is close to the currently installed generating capacity in that country [64]. Potential in the Great Lakes and in the Mexican Gulf coast are not even included in this estimate. A 98 GW portion of this capacity is located in waters shallower than 30 m. Offshore wind energy in the US. Canada also has an enormous offshore potential, in which the mean wind speed at 50 m above the ground in Canada and along its shores are good enough for big offshore wind turbines. Five important projects are competing to become the first offshore wind park in North America [65]. The Cape Wind project, located off the coast of Cape Cod in the US, would have 130 turbines totaling 420 MW. Construction is expected to begin in 2010. However, problems as regards public acceptance are manifest for this project, and might prevent its realization, and some even say, jeopardize the future of offshore wind energy in the US [66]. The Blue water Wind project [67], off the coast of Delaware, in the US, would provide this state with 600 MW of clean electricity. Construction and installation are planned from 2010. Construction of the first phase of the NaiKun project [68], in the Hecate Strait of British Columbia, Canada, is planned to begin in 2009 [8].

Ideally, offshore wind farms should be located in areas where winds blow continuously at high speeds. The new research identifies such areas and offers explanations for the physical mechanisms that produce the high winds. An example of one such high-wind mechanism is located off the coast of Northern California near Cape Mendocino. The protruding land mass of the cape deflects northerly winds along the California coast, creating a local wind jet that blows year-round. Similar jets are formed from westerly winds blowing around Tasmania, New Zealand, and Tierra del Fuego in South America, among other locations. Areas with large-scale, high wind power potential also can be found in regions of the mid-latitudes of the Atlantic and Pacific oceans, where winter storms normally track [69].

The US has been reluctant to get on board with offshore wind power, mostly because of the increased cost of offshore energy, maintenance concerns, and naysayers who think the turbines are unsightly. But with Europe expecting offshore wind to provide up to 200,000 new jobs by 2025, perhaps the US should think twice before dismissing the technology [56].

3.2.2. South America

3.2.2.1. Argentina. Argentina's long coastline and vast open expanses make it an ideal location for harnessing wind power



Fig. 19. Wind farm in Denmark [83].

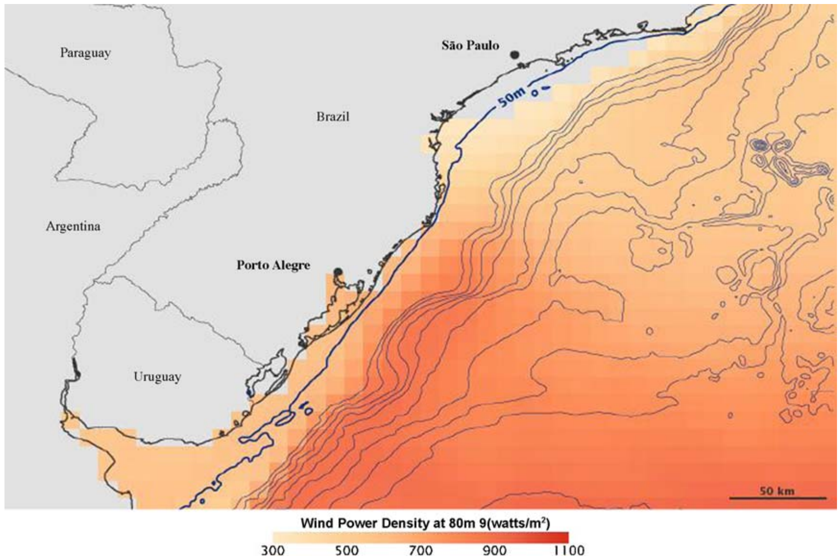


Fig. 20. Wind power for South of Brazil (acquired 1st of August 1999 to 30th of June 2007) [71].

and generating electricity, yet relatively high costs of wind turbine technology have resulted in a lack of large-scale investment in this sector. To date Argentina's ventures in harnessing wind power have taken place largely in Patagonia and also in the province of Buenos Aires. The Patagonian city of Comodoro Rivadavia derives 10% of its electrical supply from wind farms. But Argentina has a long way to go before it catches up with European countries, such as Denmark and Germany, which are the driving force in this global industry. According to the Global Wind Energy Council, Europe has a 34,205 MW capacity derived from wind power, while Central and South America have a combined capacity of 150 MW. Although wind energy requires a heavier initial investment than fossil fuel resources, generation costs have fallen by 50% over the past 15 years. The technology itself consists of wind turbines, which are large structures generating approximately 1500 kW of electricity. These installations generally consist of a tower up to 80 m in height and a rotor with a diameter starting at 60 m [70].

3.2.2.2. Brazil. To figure out whether offshore wind farms were viable, combination of satellite and buoy observations of wind speed with the specifications of currently available technology is useful. Data on water depth, which restricts where offshore farms can be located, is necessary too. This image (Fig. 20) shows the results and analysis of wind energy potential for southern Brazil. In the ocean, a series of blue lines marks ocean depths. The varying shades of orange signify wind power density, with near-red showing the greatest energy potential and near-yellow showing the smallest. Today's offshore wind turbines are better to be placed in water no more than 50 m (165 ft) deep (though floating turbines are not far off), and the turbine hubs typically operate at 80–100 m (260–330 ft) above the surface of the land or water. Consequently, the thickest blue line marks the area where wind turbines could be placed, and the wind measurements indicate wind speeds 80 m above the surface. Although wind speeds are much greater farther from shore, an area of high wind energy potential appears near the city of Porto Alegre, where wind speeds appear great enough to meet the region's energy needs – 102 GWs per year on average, compared to the need for an estimated 100 GWs in 2008 [71].

Building offshore wind farms is costlier than building land-based wind farms, but offshore farms often provide more room to accommodate large-scale projects. Equally important, much of Earth's human population lives in urban centers that hug coastlines. The coastal cities of Rio De Janeiro, São Paulo, and Porto Alegre illustrate that principle here. Pimenta's project demonstrated that an offshore wind farm would offer a clean, nearby source of energy to these heavily populated regions of Brazil [71].

3.2.2.3. Mexico. Mexico is one of the most promising areas for wind energy development in Latin America with a technical potential of as much as 40 GW. The energy regulator CRE has stated that Oaxaca's Isthmus of Tehuantepec zone has a world-class wind resource where average wind speed often exceeds 10 m/s, and the exploitable wind power potential exceeds 6000 MW. Other excellent sites are located in Baja California, Zacatecas, Hidalgo, Veracruz, Sinaloa and Yucatan. Despite this tremendous potential, wind development in Mexico has been slow, mainly due to the lack of adequate financial incentives and issues with the existing regulatory framework and policies to encourage use of wind energy. There are also other market barriers that have retarded wind development, including most recently the adverse effect of the global financial crisis. Mexico has around 50 GW of total installed electricity generation capacity, which is made up of 49% petroleum products, 21.6% hydro, 19% natural gas, 10% coal, 2.8% nuclear and 2% geothermal power. The installed and operational wind capacity was only 87 MW at the end of 2008, consisting of the state electricity company CFE's La Venta I and La Venta II projects in Oaxaca. La Venta II (83.3 MW) became operational in January 2007. In 2008, no new wind generating capacity was connected to the Mexican grid [63]. In general, Mexico is located in an area which is surrounded by waters which is capable to harness offshore winds, but an accurate wind atlas along with depth and distance of offshore farms are required.

3.3. Asia

3.3.1. China

Shanghai Donghai Bridge offshore wind farm in China with 100 MW plans to generate electricity in 2009. This project is different from a lot of offshore wind farms in Europe. The regional depth of water in that region is about 8–10 m, and distance to the coastline is 6–10 km. In 2007, a purpose for establishing a large floating offshore wind farm with 20 MW in Hainan Province, China, has been suggested, and wind turbine with vertical axis will adopted and installed 10 km away from the coastline [3]. The Chinese government has been promoting the use of renewable

energy, including wind power and solar power, amid efforts to shift from heavy reliance on coal consumption. China's installed capacity of wind power reached 2.3 million kW-h in 2006, and is expected to hit 5 million by the end of 2007. The country's installed capacities of wind power are set to reach 30 million kW-h by 2020, according to the government plan. China's offshore wind power capacities are almost three times that of onshore [72].

China's first offshore wind power station, located in Liaodong Bay in the northeast Bohai Sea, was officially put into operation late 2007. The wind power station was built by the China National Offshore Oil Corp (CNOOC), the country's largest offshore oil producer, with an investment of 40 million yuan (US$ 5.4 million). It kicked off trial operation on 8 November 2007, and has generated 200,000 kW-h of electricity by November 26. The generating unit was fixed to a jacket structure of the CNOOC's Suizhong 36-1 oil field, which is 70 km offshore in the Bohai Sea, with a 5-m-long submarine cable linking the unit with the central platform of the oil filed for power supply. This is the first wind power station in the world designed for power supply of offshore oil and gas fields. The unit is expected to reach an annual output of 4.4 million kW-h, which is equal to saving 1100 tons of diesel oil annually and also the reduction of 3500 tons of carbon dioxide and 11 tons of sulfur dioxide [72]. China is second country in Asia which has installed offshore wind turbine in order to produce electricity. It should be mentioned that China imports most of the country's need for fuel from Middle East; therefore offshore wind turbines could be helpful for economy and environmental pollution problems in this country.

3.3.2. Japan

Japan, among the world's three largest consumers of oil, is facing increasing pressure to raise its supply of energy from non-polluting sources and reduce its dependence on oil, coal and natural gas, almost all of which are imported from abroad. Fossil fuels produce two-thirds of Japan's electricity needs with other sources like nuclear and hydropower making up most of the difference. Renewable energy sources contribution to Japan's electricity needs are almost negligible [73]. Wind farms like the Nunobiki Plateau Wind Farm on a hill north of Tokyo, which generates enough electricity to power some 35,000 homes a year, have failed to make a dent in Japan's obligations to cut carbon gas emissions under the Kyoto Protocol. But Japan is now looking towards the sea, following in the footsteps of Europe which is the world's leader in wind energy, by planning a network of offshore wind farms to tap into the gales of the Pacific Ocean. Japan hopes that wind power will provide around 0.2% of the country's primary energy supply by March 2011. That figure might rise sharply if major electric companies follow through with plans to build offshore wind farms near coastal power stations. The northern Japanese city of Hokkaido, which is the first offshore wind-for-power system outside of Europe, has since 2003 been harnessing the sea breeze with two 600 kW turbines located inside a breakwater less than 1 km off the coast. That is enough to power an average of 1000 homes per year. In Europe it costs about 50–100% more to build offshore wind farms to those based on land. In Japan, it could cost even more since the island nation is surrounded by deeper seas. Japan, among the world's three largest consumers of oil, is facing increasing pressure to raise its supply of energy from non-polluting sources and reduce its dependence on oil, coal and natural gas, almost all of which are imported from abroad [73]. In Japan, the cumulative capacity of wind turbine generation systems on land has increased steadily in recent years. To install a large number of wind turbines has inherent problems such as shortage of suitable land, and inadequate infrastructure such as power cables and roads. The necessity for development of offshore wind turbine generation systems has been recognized based on the above backgrounds. It was found that there are some undesirable circumstances for offshore wind energy utilization in Japan. Technological innovation as well as an increase in scale of wind farms in order to achieve an economical profit is needed. The difficulty in realizing of offshore wind farms in Japan relates to Japanese inshore conditions, various legal regulations and fishing rights issues [74].

3.3.3. Malaysia

Aware at the potential of the harvesting the wind energy, Malaysian Government under Joint venture partnership with the State Government of Terengganu and National Electric Board in 2007 embarks on the project of integrating power supply at Pulau Perhentian (Perhentian Island). The project consists of installing two wind turbine, solar farm (Solar Panel), Generator and battery [75]. In Malaysia, study on ocean based energy sources is still in the infant stage. The annual offshore wind speed is around 1.2–4.1 m/s for Malaysian waters, with higher values occurring in the east peninsular Malaysia having 3.3–4.1 kW/m wave power. Locations situated in the South China Sea has the most promising site for wave power potential, with the highest energy resource available in the months of November to February, which coincide with northeast monsoon season. The annual wave power is below 5.0 kW/m. The offshore wind energy resource for this region also shows the same trend as the wave energy. The highest potential is in the east peninsular Malaysia with annual vector resultant wind speed of 4.1 m/s [76]. Because the annual wind speed for Malaysian water is low, therefore it does not seem to be economically feasible to construct offshore wind turbines. There are some areas which are capable of harnessing inland wind energy, but good offshore wind is not available.

3.3.4. Middle East

There has not been any offshore wind turbine in Middle East yet. There is also potential for offshore wind farms in Persian Gulf, Gulf of Oman, Caspian Sea and Arabian Sea. Future research studies regarding this issue are necessary. The term Middle East includes countries of western Asia from Iran to Israel. Iraq, Jordan, Syria, Saudi Arabia, Turkey, Kuwait, Bahrain, Qatar, UAE, and Lebanon are also major Middle Eastern countries. In some contexts, the term has recently been expanded in usage to sometimes include Afghanistan and Pakistan, the Caucacus and Central Asia, and North Africa. There has not yet been any offshore wind turbine activities in Middle Eastern waters which include Persian Gulf, Caspian Sea, Urmia Lake, Gulf of Oman, Arabian Sea, Indian Ocean, Gulf of Adan, Red Sea, and Mediterranean Sea. There has not been a serious research regarding of offshore wind turbine installation, but there is a little research work regarding of wind characteristic in these areas.

3.4. Africa

3.4.1. Egypt

Egypt enjoys an excellent wind regime, particularly in the Gulf of Suez, where average wind speeds reach 10 m/s. Egypt cooperated with Denmark to produce a Wind Atlas, issued in 1996, for the Gulf of Suez west coast. In 2003, a detailed Wind Atlas for the same area was issued, concluding that the region can host several large-scale wind farms. Since 1986 a series of large-scale wind energy projects have been built in Egypt. In 2008, 55 MW of wind power was added, bringing the total installed wind capacity up to 365 MW at the end of 2008. Several additional projects are in the pipeline. The atlas was expanded to cover the entire land area of Egypt in 2005, to establish the meteorological basis for the assessment of wind energy resources all over Egypt. The atlas indicates that large regions of the eastern and western deserts of

the Nile River and parts of Sinai have average annual wind speeds of 7–8 m/s [77]. There has not been any offshore wind farm in Egypt yet, but more research must be done in the future for purpose of harnessing offshore wind energy in regions with high capacity.

3.4.2. South Africa

The Jeffreys Bay area currently suffers from power cuts and the objective of the proposal according to Mainstream is to help stabilize energy supply to the area. A stable energy supply as well as stabilization of the grid will assist the local economy in developing a greater degree of energy security. The project has the potential to produce enough green energy to power approximately 200,000 households [78]. The Jeffreys Bay wind farm project was started on early October 2009 in order to provide 100 MWs of electricity for this area, but there has not been any offshore wind farm in this country.

3.4.3. Morocco

Morocco, like Egypt, has excellent wind conditions with average wind speeds of 7.5–9.5 m/s in the south and 9.5–11 m/s in the north. The Moroccan government has plans to expand its current wind energy capacity from 124 to 1000 MW by 2012. Several regions have been identified as having potential to help the government reach its goal. These regions include the greater Tangier, Ksar Sghir, and Tétouan areas. These areas have an average annual wind speed of 8–11 m/s at a height of 10 m. Other areas include the Dakhla, Laâyoune, Tarfaya, and Essaouira areas where the wind speed ranges from 7 to 8.5 m/s [79]. Morocco has a great potential of in-land wind energy, therefore it could be a reason for lack of offshore wind turbine development in this country.

3.5. Pacific

3.5.1. Australia

Although numerous offshore wind farms have been constructed in EU and USA, no such a facility is available in Australia. Development of green (renewable) energy has been recognized as an alternative and favor option in Australia. It is expected that offshore wind energy will be an important renewable energy in Australia in the next decade. Thus, it is desired to develop the technique of offshore wind farms now [80]. Australia has some of the world's best wind resources, and benefits from a stable, growing economy and good access to grid infrastructure. After a couple of years of slow growth in Australia's wind market, the speed of development picked up again in 2008, with 482 MW of new installations, a 58% leap in terms of total installed capacity. Australia is now home to 50 wind farms, with a total capacity of 1306 GW [77]. Fig. 10 shows a rough estimate for monthly wind speed, it shows that there is wind speed of between 10 and 17 m/s in southern waters of Australia. It goes without saying that depth of water in this region must be measured for further research in order to think about offshore wind farms.

3.5.2. New Zealand

New Zealand has an excellent wind resource, which is largely untapped. A study completed for the Electricity Commission (New Zealand's electricity market regulator) indicated that the country's economic wind resource is sufficient to meet annual demand several times over. The study identified that areas with an annual wind speed of greater than about 8.5 m/s have the potential to generate over 50,000 GWh per year. An even larger resource was identified in the next band of wind speed, from 7.5 to 8.5 m/s. New Zealand's total electricity generation in 2007 was 42,374 GWh. New Zealand's installed wind energy capacity grew from 322 to 325 MW during 2008. This small growth in installed capacity, however, does not adequately reflect the wind industry's activity over the year: while only 3.5 MW were installed, a further 187 MW are now under construction. Meridian Energy's Project West Wind (142 MW), near Wellington, is expected to and be completed by the end of 2009. The completion of the Te Rere Hau wind farm (48.5 MW) will see New Zealand's installed wind capacity pass the 500 MW in early 2010 [77].

4. Global wind power resources

Because electricity is lost as it is carried long distances, we begin an evaluation of the world wind by looking at where people use electricity. As a first-order approximation of where power is currently needed, NASA examines the earth at night. The image reveals that the electric-using population is concentrated in a few world areas and is mostly along the coasts. The map below (Fig. 21) is a world, year-round average wind speed map. It is derived from 10 years of GEOS-1 satellite data. Satellite data are the only wind data with global extent, but are less accurate because the data are indirect. Roughly 7 m/s and faster are economically worth exploiting today even in higher-cost offshore locations; those are the orange, pink, and shades of red and brown in the figure. In many areas, especially on land, the 6 m/s areas are already economically viable, those are the yellows. We see that the largest wind resources are above the oceans and mid-continental plains of each of the major continents. The coastal oceans are of special interest because they have strong winds and, as seen by the earth at night, they are close to most of the world's population and electric use [81].

Globally, the wind resources are very large and it is estimated to be 72 TW which is seven times the world's electricity demand and five times the world energy demand. Since fossil fuel creates carbon dioxide and is the main pollutant of the environment, wind energy could be a perfect substitute for solving this problem.

4.1. Advantages of offshore turbines

Onshore wind energy has grown enormously over the last decade to the point where it generates more than 10% of all electricity in certain regions (such as Denmark, Schleswig-Holstein in Germany and Gotland in Sweden). However, this expansion has not been without problems and the resistance to wind farm developments experienced in Britain since the mid 1990s, is now present in other countries to a lesser or greater extent. One solution, of avoiding land-use disputes and to reduce the noise and visual impacts, is to move the developments offshore, which also has a number of other advantages [7]:

- Availability of large continuous areas, suitable for major projects;
- Higher wind speeds, which generally increase with distance from the shore;

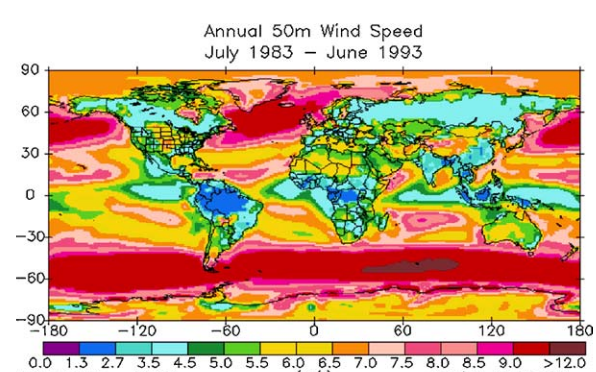


Fig. 21. Annual global wind speed at 50 m from July 1983 to June 1993 [81].

- Less turbulence, which allows the turbines to harvest the energy more effectively and reduces the fatigue loads on the turbine;
- Lower wind-shear (i.e. the boundary layer of slower moving wind close to the surface is thinner), thus allowing the use of shorter towers.

5. Manufactured offshore wind turbines

Here there are different models of wind turbines which were built for offshore installation. For resource estimates, water depth is also very important; this is really dependent on the tower design not the wind turbine and nacelle, although the turbine manufacturer would have to approve the tower. There are some turbines that are designed big enough to be economically feasible for offshore use [82]:

5.1. Vesta 90

It has the capacity of 3 MW, rotor diameter of 90 m and hub height of 80–105 m. Vestas has by far the most experience with multi megawatt machines offshore. Many V90s are currently operating offshore. Thirty of V90s are at Kentish flats since Aug 2005, thirty at Barrow since May 2006 and 36 at Egmond Ann Zee off Egmond, Netherlands since Nov 2006.

5.2. REpower 5M

It has the capacity of 5 MW, rotor diameter of 126 m and hub height of 90 m. Two of these units are working at Beatrice in United Kingdom since August 2007.

5.3. Siemens SWT-3.6-107

It has the capacity of 3.6 MW, rotor diameter of 107 m and hub height of 83.5 m. It has been operating in Burbo Bank and Liverpool Bay since October 2007.

5.4. General Electric 3.6 sl (discontinued)

It has the capacity of 3.6 MW, rotor diameter of 111 m and hub height of 75 m. Seven of these turbines have been operating in Arklow Bank of Ireland since Jun 2004.

6. Wind maps created by QuickSCAT [83]

The new maps created by QuickSCAT have many potential uses including planning the location of offshore wind farms to convert wind energy into electric energy. Ocean wind farms have less environmental impact than onshore wind farms, whose noise tends to disturb sensitive wildlife in their immediate area.

QuikSCAT, launched in 1999, tracks the speed, direction and power of winds near the ocean surface. Data from QuikSCAT, collected continuously by a specialized microwave radar instrument named SeaWinds, also are used to predict storms and enhance the accuracy of weather forecasts. Wind energy has the potential to provide 10–15% of future world energy requirements, according to Paul Dimotakis, chief technologist at JPL. If ocean areas with high winds were tapped for wind energy, they could potentially generate 500–800 W of energy per square meter, according to Liu's research. Dimotakis notes that while this is slightly less than solar energy (which generates about 1 kW of energy per square meter), wind power can be converted to electricity more efficiently than solar energy and at a lower cost per watt of electricity produced. The new QuikSCAT maps, which add to previous generations of QuikSCAT wind atlases, also will be beneficial to the shipping industry by highlighting areas of the ocean where high winds could be hazardous to ships, allowing them to steer clear of these areas.

Scientists use the QuikSCAT data to examine how ocean winds affect weather and climate, by driving ocean currents, mixing ocean waters, and affecting the carbon, heat and water interaction between the ocean and the atmosphere.

7. Public attitudes

Although there is a rich literature on the benefits of local control and a concern for the impact of wind power structures on cultural landscapes [84–86], less is known about which factors influence support and opposition to sea-based wind power structures [84,87].

Public opposition has derailed many land-based wind power projects throughout the world [84,88]. Recently, the first offshore wind proposal in North America, in Nantucket Sound (MA, USA) has generated a strong opposition movement, and a seemingly more modest movement of supporters [84].

Attitudes of the public as such are not the issue, because on the average general attitudes towards wind powers are very positive [89–93]. The fact that a minority does not support wind power is not surprising because there is hardly anything in life that is universally supported. The existence of opponents is merely a fact of life and, furthermore, it may be rooted in fundamental arguments concerning landscape characteristics and community identity [89,94,95].

It is interesting to know that there are not any opposition movements against wind turbine installation (on or off shore) in many countries located in Africa, Middle East and South America. It goes without saying that opinions and attitudes of people about wind power are not basically same as their attitudes about wind farms. Oppositions consider different factors like marine life, environmental impacts, noise pollution, aesthetic of ocean view, tourism industry and so on. There has not been any survey in Iran regarding of the public attitude regarding of turbine installation in general. But people in Iran support any action which yields to cleaner environment. For instance there are many big installed turbines in city of Manjil in north of Iran, but there has not been any opposition movements or demonstrations regarding of turbine existence in the city. There has not been any plan about offshore wind turbine in Iran yet, but it is easy to predict the attitude of people regarding of this matter. People have shown their positive supports toward any kinds of renewable energy installations.

8. Power

Offshore winds are generally stronger and more constant than onshore winds. As a result, turbines are expected to operate at their maximum capacity for a larger percentage of the time, and the constancy of wind speed reduces wear on the turbine and provides a more constant source of power to the electrical grid reducing the need for other sources of electricity to serve as backups [96]. The increase in wind speed leads to a 150% increase in electricity production for offshore wind turbines [97] and an increase in the capacity factor of the wind farm from about 25 to 40% [98]. It is economically feasible to construct offshore wind turbine facilities, but we must consider other factors which cause problem toward offshore wind turbine installation. It needs high technology and higher initial investment for that purpose.

9. Distance to the shore

The distance to shore influences both the construction and operation and maintenance costs. During construction the ships

will have to make a number of trips between the site and shore to load additional equipment. This travel period is costly and therefore the closer an offshore site is to an industrial port facility, the less expensive installation will be. Furthermore, the distance to shore also dictates the amount of transmission cabling required. During operation a maintenance crew will need to make regular trips to the wind farm to monitor the foundations, towers and turbines [99]. Locating this crew as close as possible to the wind farm will decrease both the environmental impacts and the costs of maintenance [6].

For offshore wind turbine installation, all the factors must be considered in order to achieve the best and optimum results. In some regions, the offshore wind farms must be placed inside the ocean because of the high wind potential. For majority of installed turbines in UK (Table 2), distance to the shore is less than 5.5 km, but there are only two turbines which are located at the distance of 25 km from the shore. Netherlands has installed 128 offshore wind turbines in which 60 of them have been installed at the distance of 23 km from the shore. Denmark has installed 204 offshore turbines in which most of them are located at the distance of less than 10 km, but maximum distance is 20 km from the shore.

10. Depth for offshore wind turbine foundation

Extensive shallow regions, less than 20 m deep, are found along the coast of United Arab Emirates (hereafter referred to as Southern Shallows), around Bahrain, and at the head of the Persian Gulf. Deeper portions, bigger than 40 m deep, are found along the Iranian coast continuing into the Strait of Hormuz, which has a width of 56 km and connects the Persian Gulf via the Gulf of Oman with the northern Indian Ocean. Tectonic driven subsidence deepened the seafloor of the Strait on its southern side (200–300 m depths are seen in some localized seafloor depressions) and produced a 70–95 m deep trough along the Iranian side of the eastern part of the Persian Gulf. A southward widening channel leads from the Strait south across a series of sills (water depth of 110 m) and shallow basins to the shelf edge [24]. The maximum depth and average depth of the Urmia Lake respectively are 16 and 5 m [100]. It goes without saying that depth of water in Gulf of Oman is less than 300 m which is feasible for offshore turbine installation. The southern part of Caspian Sea includes the South Caspian Depression with its deepest point being 1025 m below the surface [34]. In offshore wind the term "deepwater" generally refers to water depths of more than 30 m.

For majority of installed turbines in UK, depth of water for most of the offshore wind sites are less than 23 m. Netherlands has installed 128 offshore wind turbines in which 60 of them have been installed at the distance of 23 km from the shore with depth of between 20 and 24 m, but 68 of them have depth of less than 22 m. Denmark has installed 204 offshore wind turbines in which 80 of them have depths of less than 12 m, but majority of them have been installed at depths of less than 9.5 m. Sweden, Ireland and Germany with total amount of 14, 7 and 2 installed offshore wind turbines respectively are other European countries in this field in which majority of them have been placed in areas with depths of less than 4.5 m (Table 2).

11. Floating wind turbine concept

The concept of floating wind turbine is at its early stage, but there are many research works in order to make this idea implementable and also economical for harnessing great amount of energy far out in the deep oceans. It should be noted that it is not economically feasible to construct turbine structures in very deep waters; also a very sophisticated technology would be required for this purpose. The best proposed solution is to investigate floating concept in which the weight of turbine structure would be then carried by the buoyancy force.

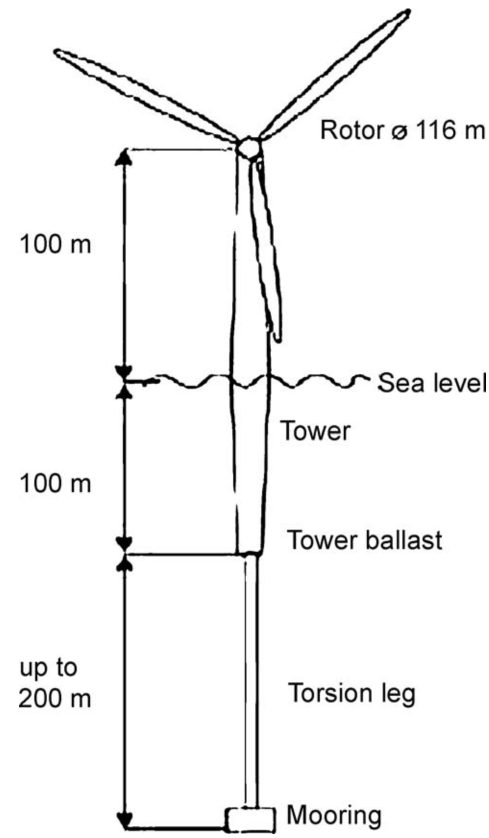


Fig. 22. Floating windmill according to Sway concept [102].

A development in wind energy technology towards higher nominal power of the wind turbines is related to the shift of the turbines to better wind conditions. After the shift from onshore to offshore areas, there has been an effort to move further from the sea coast to the deep water areas, which requires floating windmills [101].

The specifications for the floating wind mill were provided by Sway. Further information was obtained from its suppliers. Nexans [102] produces offshore cables and Multibrid [103] produces the wind turbine. Fig. 22 illustrates the power plant, which is designed to be installed at a depth of 100–300 m, and up to 50 km from the coast. This ensures the windmills cannot be seen or heard from the shore [104,102].

The tower is submerged under the sea level. The bottom part is filled with olivine ballast and helps to balance the windmill. The upper part under the sea level is filled with air and serves to float the windmill. There is one mooring point created from stones on the sea bottom and the windmill is connected to it by a torsion leg. The structure above the sea level is the tower with the wind turbine on the top [104,102].

NREL, together with MIT, is studying a Tension Leg Platform for a floating wind turbine. The corners of their platform, designed for water depths from 60 to 200 m and for a 5 MW turbine, would be connected by pre tensioned mooring lines anchored to the seabed by suction piles. The pretension in the lines is intended to stabilize the turbine in heave, pitch and roll. Dynamic modeling of this concept in wind and wave conditions has already been made with promising results [8,105]. A half-scale prototype of this system is hoped to soon be installed in the US [8,106]. This concept could be used for depths of 60–200 m, but there is another concept (Ballast Stabilized) which could be used for water depths from 200 to



Fig. 23. Vessel carrying the blade for installation [107].

700 m. But extreme wave condition for these concepts remains the major problem which must be solved by many researches in the future. The average depth of the Persian Gulf is 36 m; therefore there is not any need for floating wind turbine system. For Caspian Sea, there are some areas with depth of more than 1000 m which is difficult and costly to use anchor in order to support the structure. But there are some areas in Caspian Sea with depth of less than 200 m which are suitable for floating turbines. Depth of water in the Gulf of Oman is up to 300 m which is also suitable for floating turbines too. But maximum depth of water in Urmia Lake is 12 m which is not necessary for floating turbines.

12. Challenges facing offshore wind energy

Offshore wind power has both positive and negative environmental consequences. The negative environmental consequences are generally local, whereas the positive environmental consequences are global and exist only insofar as offshore wind power displaces other forms of electricity generation [6]. Several challenges are, however, met by offshore wind energy. Higher investments in towers, foundations and underwater cabling are needed, and installation is more difficult (Fig. 23) and expensive offshore. Offshore wind energy is also 1.5–2 times more expensive than onshore as of now [8,108].

Repairs are an estimated 5–10 times more expensive to perform offshore than onshore, mainly due to the need for expensive crane vessels [109], and waiting periods for suitable weather conditions can be extremely costly. In some cases, even for a turbine located only 1 km offshore, a period as long as 2 weeks can pass without access to the site for repair being possible [8,110]. One conclusion from this experience and from other wind parks is that the wind turbine technology should be proven before turbines are taken offshore [8,111]. Purchasing a special purpose crane vessel to perform maintenance could for example be an option, in which case the vessel could also be used for installation purposes [112]. Specifically, access solutions less dependant on wind and wave conditions are recommended [113].

Another challenge facing offshore wind energy systems is the risk for a shortage of vessels for construction and repair purposes, as in the coming years, the expected fast increasing construction of offshore wind farms is expected to begin competing with repair work [8,111]. It goes without saying that repair and installation of the offshore wind turbines for Iran would be very difficult in Persian Gulf and Gulf of Oman, because of need for large cranes specially during the repair periods. For this case it would be better for Iran to purchase crane and vessel for this purpose. Caspian Sea and Urmia Lake have bigger problems, because they do not have access to open sea. There is no way to bring cranes and vessels for installation or repair of the turbines from major countries in this profession.

13. Economic issues

Several studies have been carried out on the technical and economical assessment of offshore/onshore wind farms. Pantaleo et al. [115] have concluded that large wind farm investments present internal rate of return (IRR) value of 27%, in the technical and economical feasibility study of offshore wind farms in the Region of Puglia, Italia. Stocton [114,116] has revealed that wind farm delivers electricity at a price 34% less than residual fueled generation, in an economic feasibility study of a utility-scale wind farm in Hawaii, USA. El-Sayed's study [114,117] has indicated that the cost/benefit analysis would be less than unity for a planned wind farm in Za'afarana, Egypt. Marafia and Ashour [114,118] have presented that the cost of electricity generation from the wind which can be as low as 0.0289 h/kWh compares favorably to that from fossil fuel resources, in the potential and economical feasibility study adopting wind energy in Qatar. El-Osta and Kalife [114,119] have demonstrated that the proposed wind farm in Zwara, Libya was economically feasible for the different wind turbine sizes of 0.6, 1, and 1.5 MW. Cavallaro and Ciraolo [114,120] have shown that the wind farm located in the island of Salina, Italy was an attractive and realistic option. An integrated time-depending feasibility study on behavior of wind farms in Greece has concluded that the electricity price escalation and inflation rates are the most important parameters of the feasibility analysis [114,121]. It goes without saying that offshore wind industry has not been taken seriously around the globe except in Northern Europe and also Northern America.

The development of off shore energy facilities takes place in an economic as well as a legal and physical environment. When market conditions do not support such development, public policies in the form of economic approaches (e.g., through taxes, subsidies, and transaction systems) make offshore wind energy production more attractive. Economic approaches are frequently used as a means of achieving mandated quotas [122] or in conjunction with other coercive regulatory instruments [123–125].

The economic feasibility of a wind farm is decisive. If the wind farm is found not to be economically feasible, the project should not be begun at all. In calculating the economic feasibility over a period of around 20 years of operation, various cost items (such as actual energy yield, repairs, etc.) must be taken into consideration even though they cannot be forecast with certainty. On the one hand, investment costs are a crucial factor in determining feasibility; they mainly depend on the cost of the wind turbines themselves and on operating costs. On the other hand, the income generated by the electricity fed to the grid at a defined feed-in tariff is also decisive. Here, a long-term power purchase agreement (PPA) with fixed rates should be signed if possible. The financing for the project can only be considered ensured if the term of this PPA is long enough (generally at least 10 years). In assessing economic feasibility, the cost of operation (maintenance, repairs, insurance, etc.) and provisions for the dismantling of the wind turbines must be calculated prudently already in planning. Otherwise, it is not likely that investors and banks will be convinced of the project's financing, nor that the operation of the wind farm can be economically secured. However, if all of these steps in the planning of the wind power project are successful, the project can be implemented and put into operation [126]. Even if a renewable energy project would not be economically feasible now, but theses projects must be implemented in order to supply the energy demands of the future human being.

14. Conclusion

Offshore wind energy is a promising frontier for generating electricity in many countries. Offshore wind farms have been considered to be one of the main sources of harnessing energy for

many European countries particularly north Europe because of high offshore wind capacity. However, due to the limitation of land-use for onshore wind farms in many countries, offshore wind energy promises to become an important source of energy in future. It should be noted that limited land area is another reason for offshore wind technology in North Europe. Offshore wind power generation is expanding on an almost global scale. There are many countries like Iran with offshore wind potential, but there has not been serious effort in this regard. As the best wind resources become developed onshore, there has been increasing effort toward offshore wind industries. Despite the moderate wind resource found in Iranian waters, using existing technologies, offshore wind power can contribute a significant share of the country's electricity supply. The results indicated that Iran's offshore resources are promising, situated close to the densely populated islands and coastal cities along the coastlines of Persian Gulf, Caspian Sea and Gulf of Oman. Offshore wind energy can be used to combat air pollution, expand electricity production and create jobs. It is also important to do more research to provide accurate offshore wind atlas for locating the best sites for turbine installation in Iran.

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